Plasma Wakefield Acceleration
and
AWAKE

CAS, Ferney-Voltaire
May 13, 2022

Edda Gschwendtner, CERN

Outline

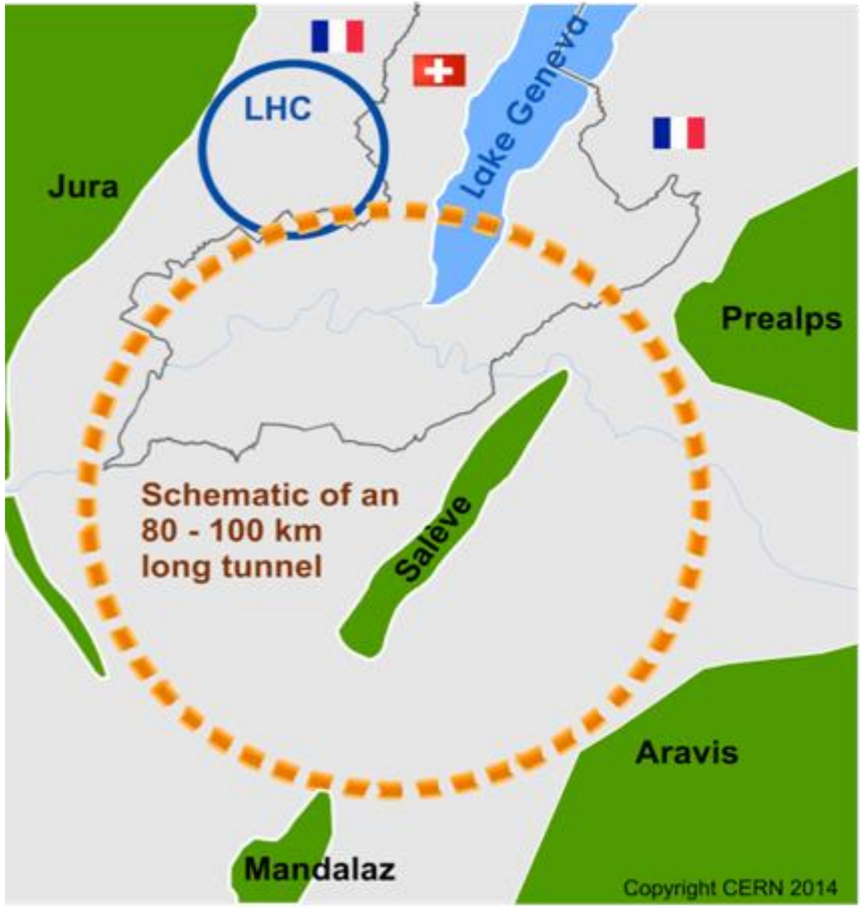
- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment
- Applications with AWAKE-Like Scheme
- Outlook

Discover New Physics

Accelerate particles to even higher energies

→ **Bigger accelerators: circular colliders**

Future Circular Collider: FCC



Limitations of conventional circular accelerators:

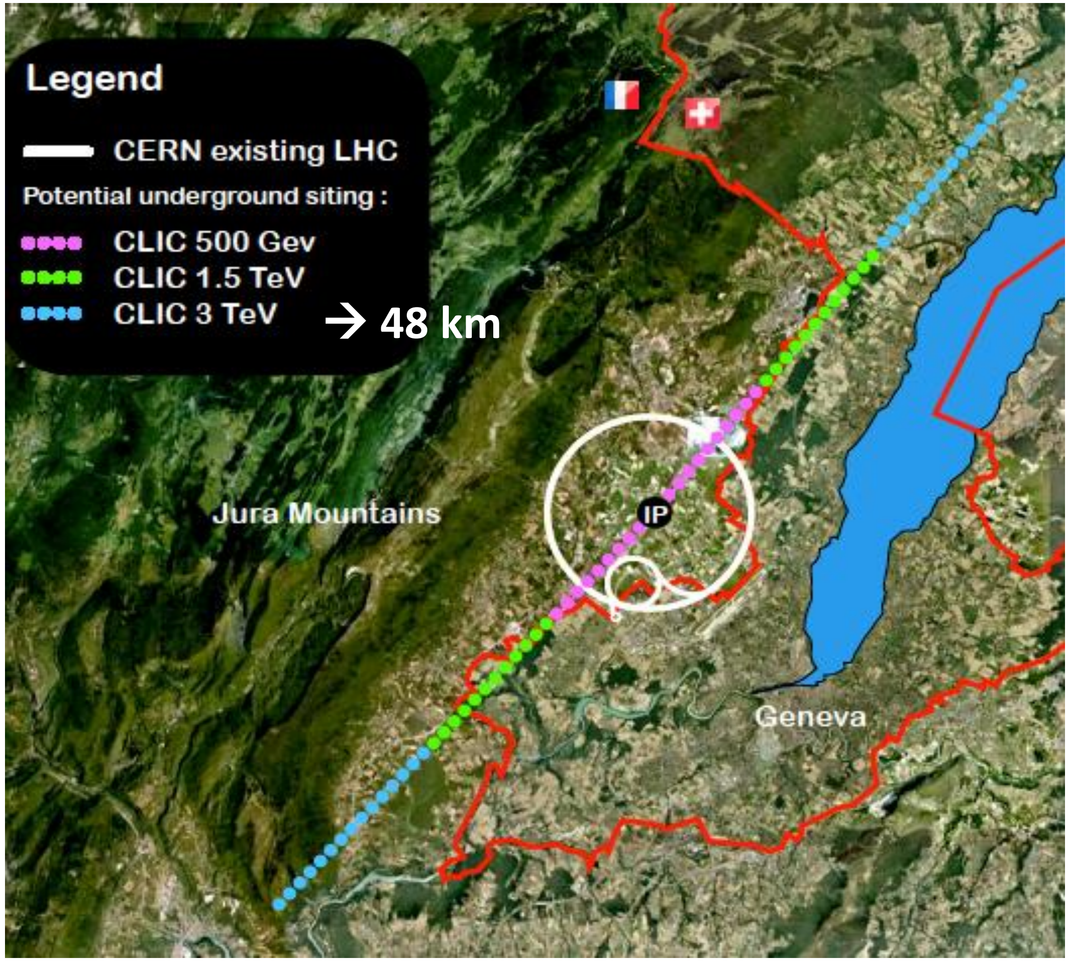
- For **hadron colliders**, the limitation is **magnet strength**. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach **100 TeV** proton-proton collision energy.
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of positron colliders. These machines are unfeasible for collision energies beyond **~350 GeV**.

$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$

Discover New Physics

Linear colliders are favorable for acceleration of low mass particles to high energies.

CLIC, electron-positron collider with 3 TeV energy

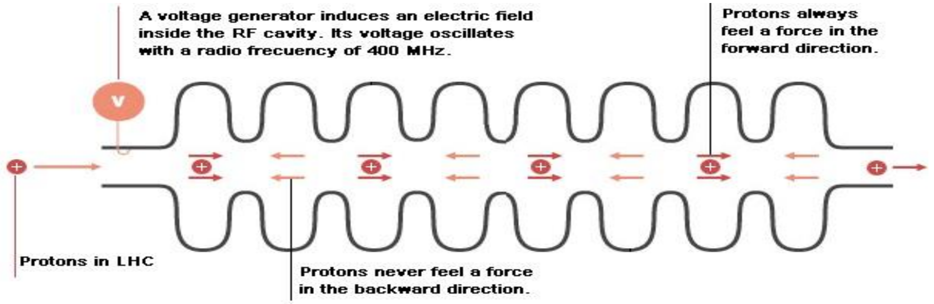


Limitations of linear colliders:

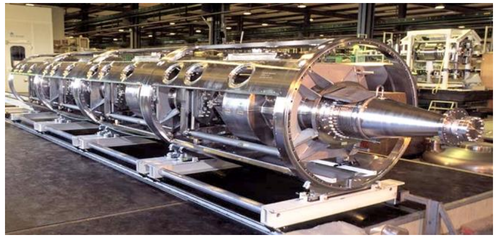
- Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.

Why Plasma Wakefield Acceleration?

Conventional Acceleration Technology: Radiofrequency Cavities

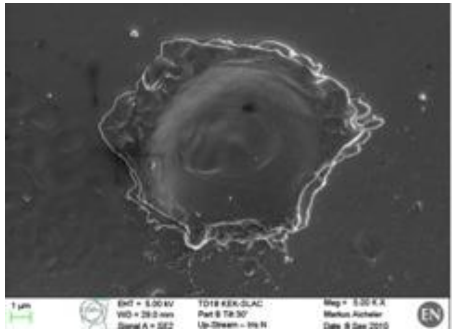


LHC Cavity



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.
- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m
- However, accelerating fields are limited to <100 MV/m
  - In metallic structures, a too high field level leads to break down of surfaces, creating electric discharge.
  - Fields cannot be sustained; structures might be damaged.



- several tens of kilometers for future linear colliders

Plasma Wakefield Acceleration

➔Acceleration technology, which obtains ~1000 factor stronger acceleration than conventional technology.

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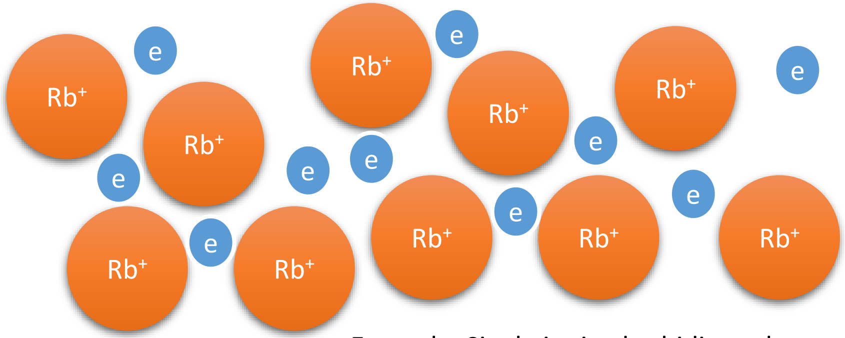
Plasma Wakefield

What is a plasma?



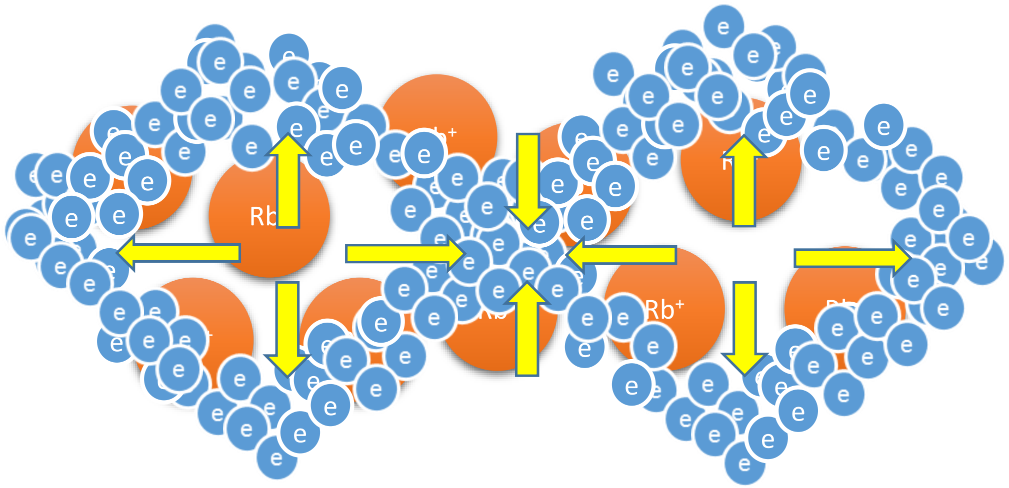
Example: Single ionized rubidium plasma

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?



Fields created by collective motion of plasma particles are called plasma wakefields.

Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

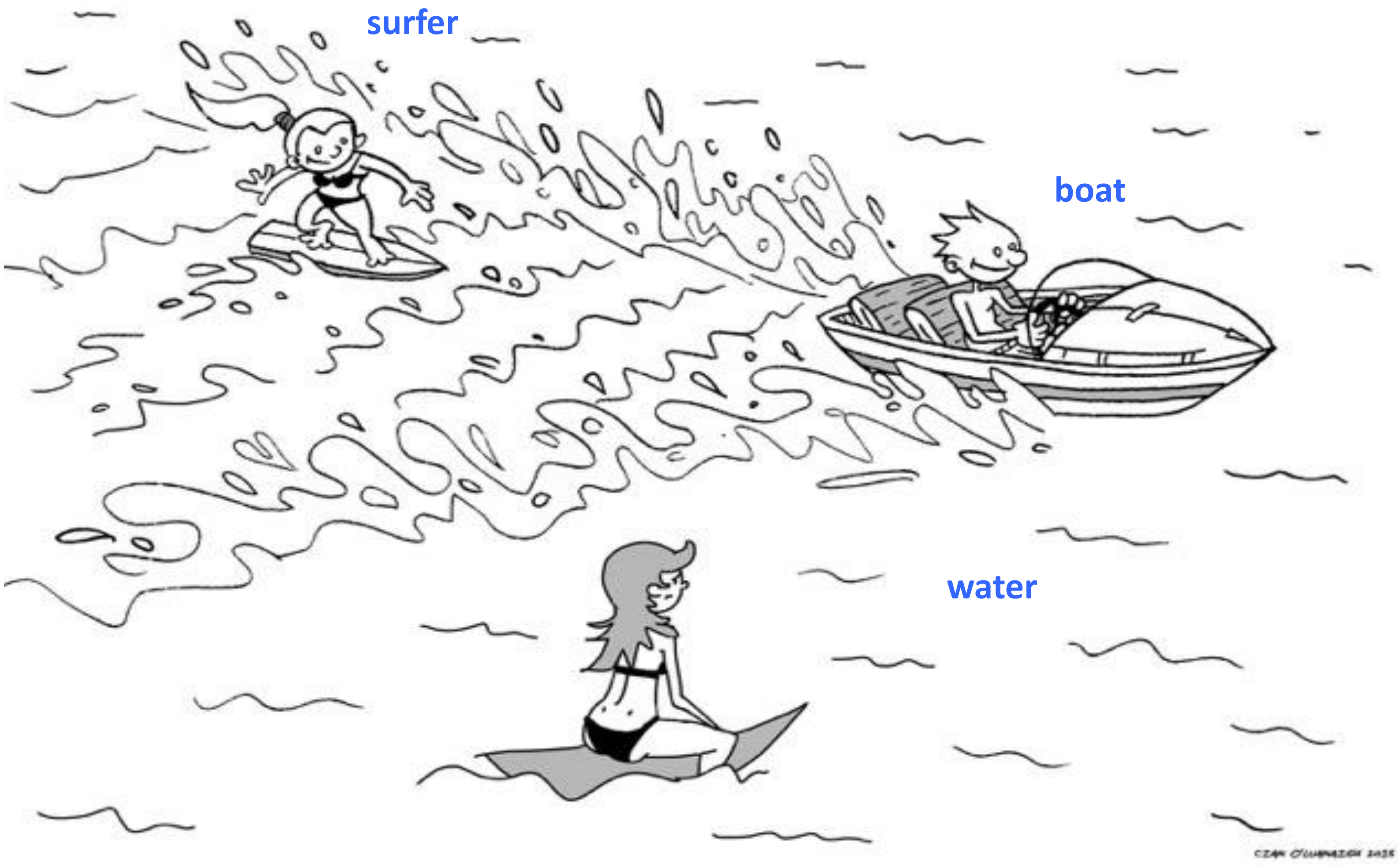
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2.

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

How to Create a Plasma Wakefield?



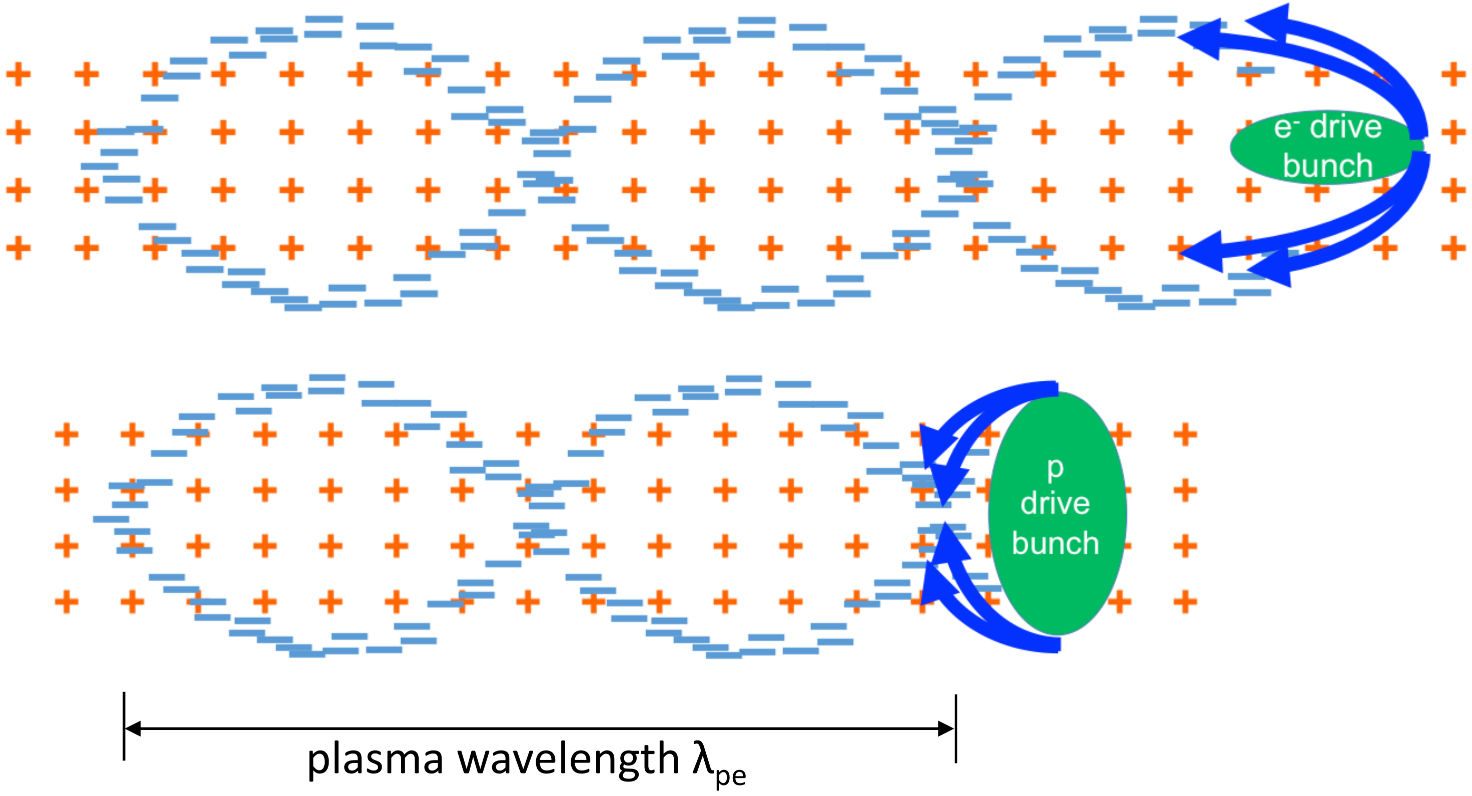
Analogy:
water → plasma

Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

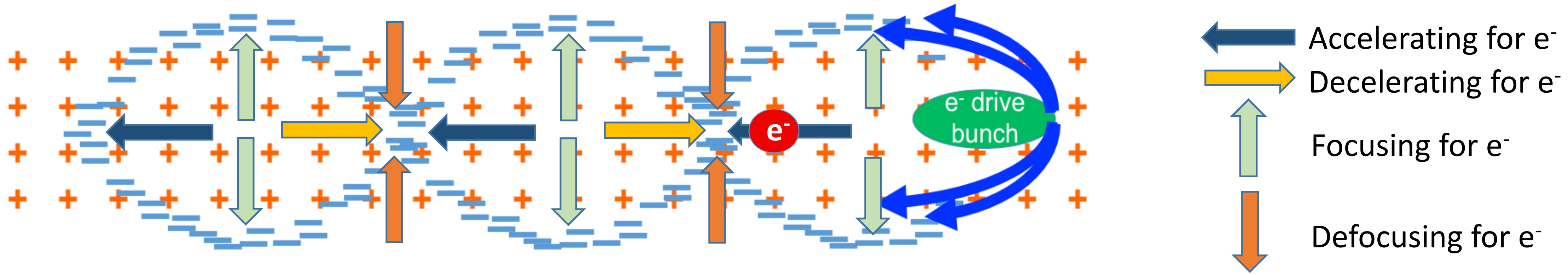
Principle of Plasma Wakefield Acceleration

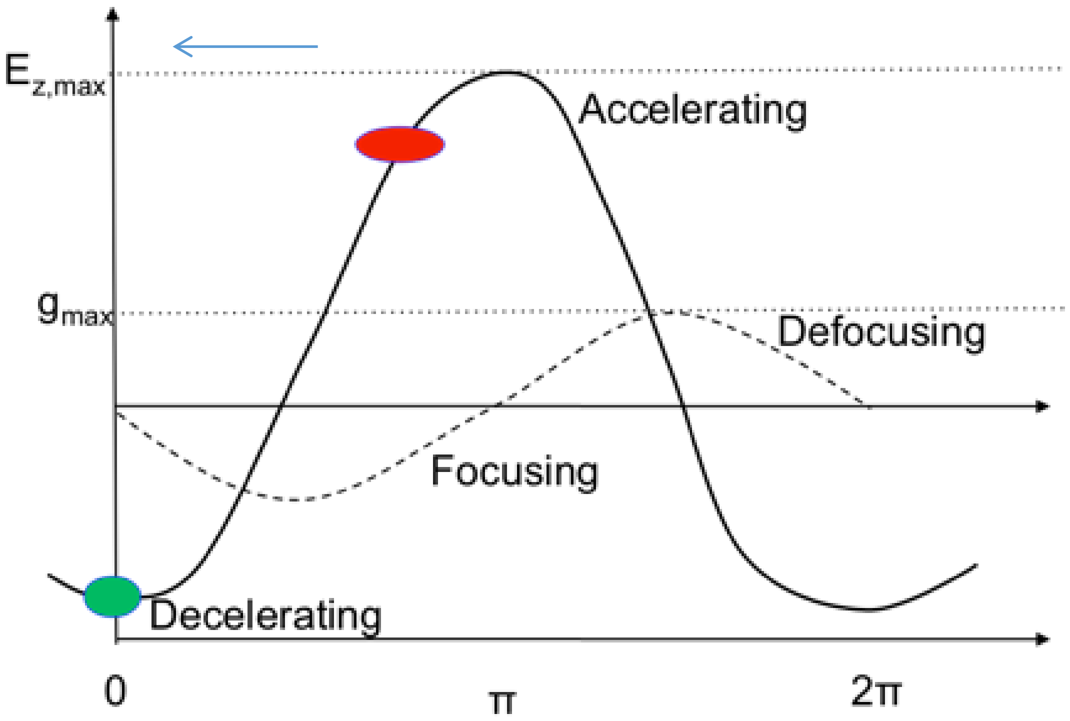
- Laser drive beam
  - ➔ Ponderomotive force
- Charged particle drive beam
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?





Plasma Baseline Parameters

- A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \quad \rightarrow \quad \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \qquad k_{pe} = \frac{\omega_{pe}}{c}$$

Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE) → ω_{pe} = 1.25x10^{12} rad/s → $\frac{c}{\omega_{pe}}$ **= 0.2mm** → k_{pe} = 5 mm^{-1}

- This translates into a wavelength of the plasma oscillation

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \quad \rightarrow \quad \lambda_{pe} \approx 1\text{ mm} \sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_{pe}}}$$

λ_{pe} = 1.2 mm → **Produce cavities with mm size!**

Accelerating Field, Energy in PWA

The maximum accelerating field (wave-breaking field) is:

$$e\,E_{WB} = 96\ \frac{V}{m}\sqrt{\frac{n_{pe}}{cm^{-3}}}$$

Example: $n_{pe} = 10^{16}\ cm^{-3} \rightarrow E_{WB} = 10GV/m$

Increase gradient by increasing density.

➔ Advantage of beam-driven PWFA

➔For LWFA: **dephasing**: laser group velocity depends on plasma density, is slower than c.

- Electron energy reach is limited by dephasing: → move to lower densities and longer accelerators
- Lower density needs higher laser power (Significant progress since Chirped Pulse Amplification, CPA, Nobel Prize 2018 to D. Strickland & G. Mourou)

Drive beams:

In order to create plasma wakefields efficiently, the drive bunch length has to be short compared to the plasma wavelength.

→ Relatively easy for **Laser** and **Electron** bunches.

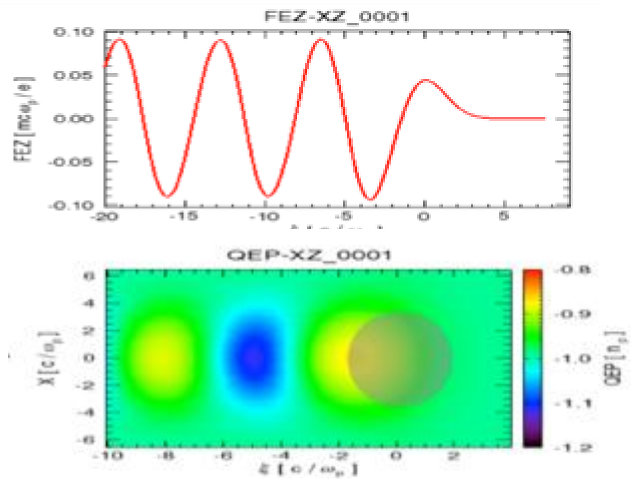
→ **Proton** beam relies on Self-Modulation.

$$E_{acc} = 110\ \frac{MV}{m}\ \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6mm)^2}$$

Beam Quality in PWA

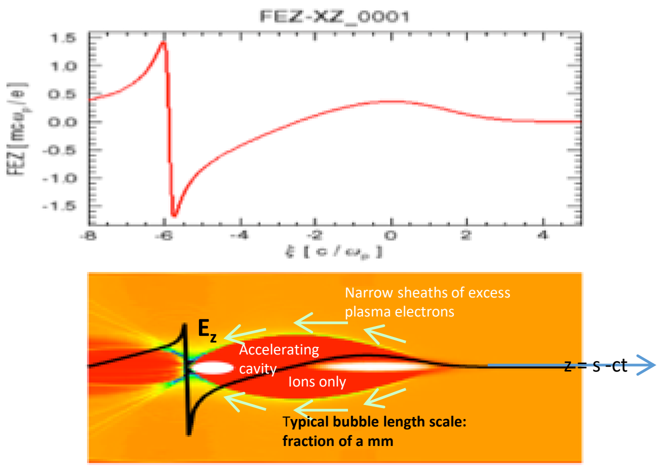
Different regimes:

Linear regime: $n_{beam} << n_{pe}$



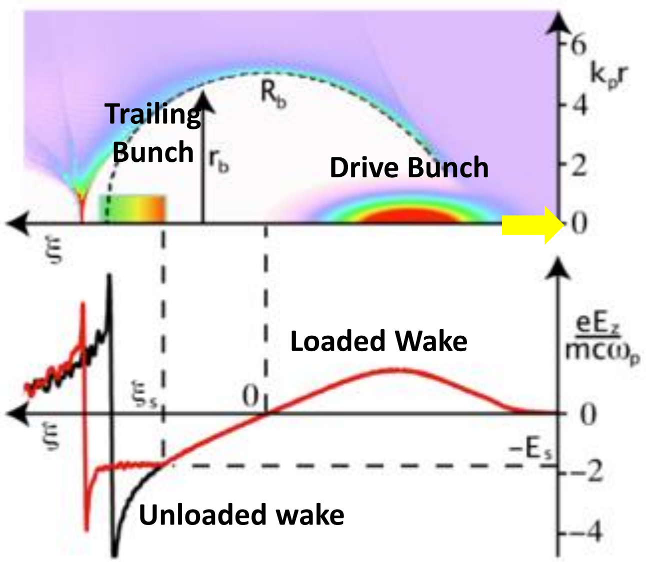
- *lower wakefields*
- *transverse forces not linear in r*
+ Symmetric for positive and negative witness bunches
+ Well described by theory

Blow-out regime: $n_{beam} >> n_{pe}$



+ Higher wakefields
+ transverse forces linear in r (emittance preservation)
+ High charge witness acceleration possible
- *Requires more intense drivers*
- *Not ideal for positron acceleration*

Beam loading



Sufficient charge in the witness bunch to flatten the accelerating field

→ **reduce energy spread**

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

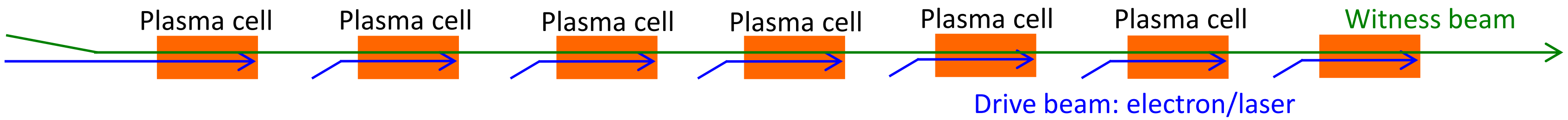
Electron drive beam: 30 J/bunch

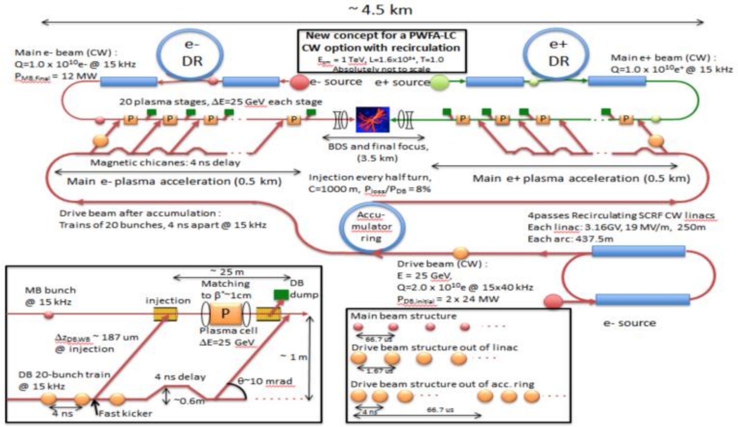
Witness beams:

Electrons: 10^{10} particles @ 1 TeV ~few kJ

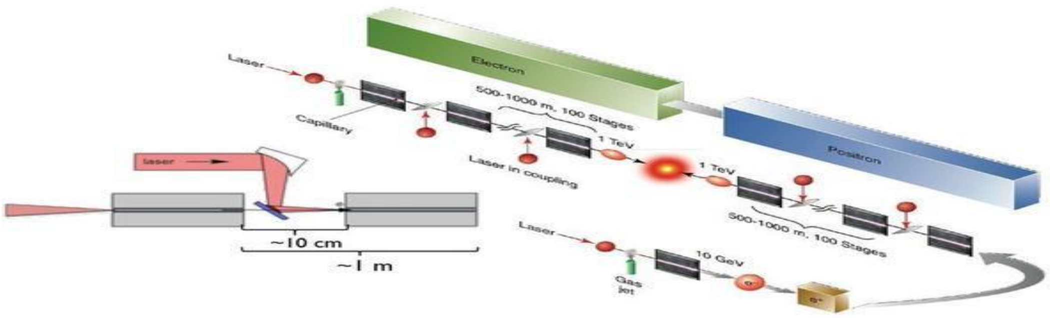
To reach TeV scale:

- **Electron/laser driven PWA**: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….





E. Adli *et. al*.,arXiv:1308.1145 [physics.acc-ph]



C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:

Electrons: 10^{10} particles @ 1 TeV ~few kJ

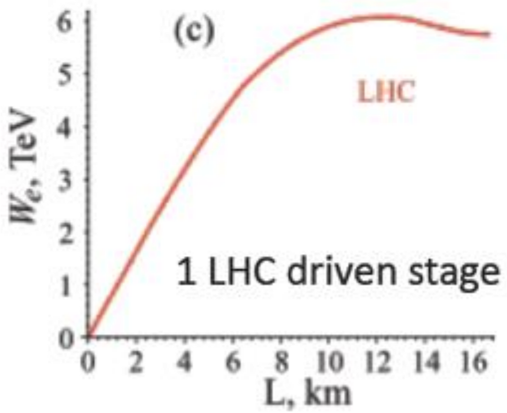
- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

Dephasing:

SPS: ~70 m

LHC: ~few km

FCC: ~ ∞

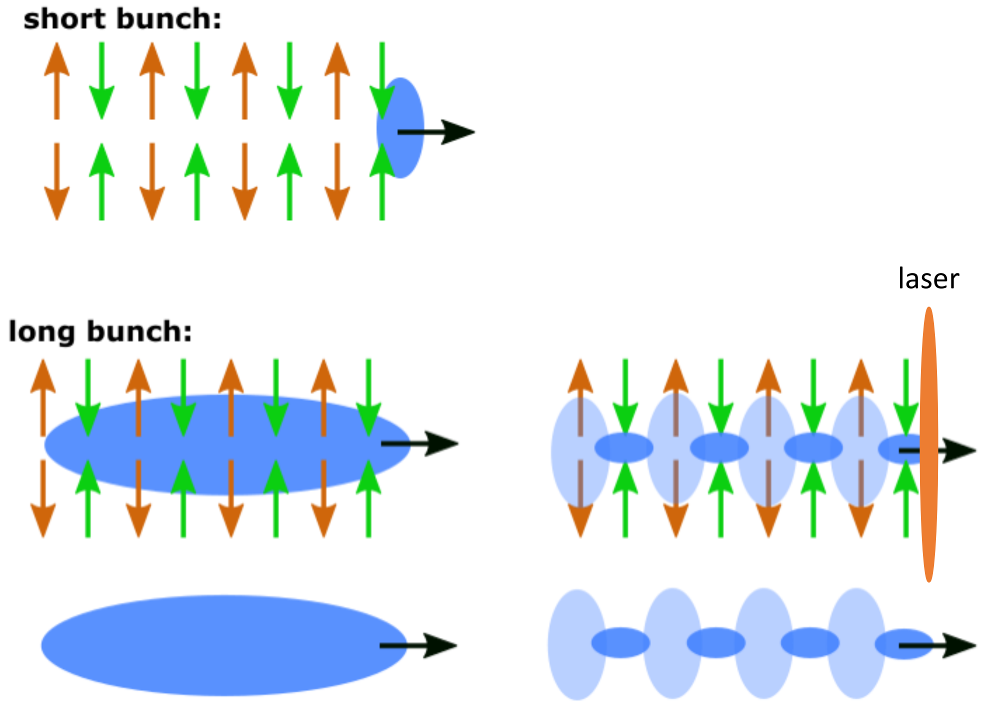


Seeded Self-Modulation of the Proton Beam

In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.

CERN SPS proton bunch: very long! (**σ_z = 12 cm**) → much longer than plasma wavelength (**λ = 1mm**)

N. Kumar, A. Pukhov, K. Lotov, PRL 104, 255003 (2010)



Self-Modulation:

a) Bunch drives wakefields at the initial seed value when entering plasma.

- **Initial wakefields act back** on the proton bunch itself. → On-axis density is modulated. → Contribution to the wakefields is $\propto n_b$.

b) Density modulation on-axis → **micro-bunches**.

- Micro-bunches separated by plasma wavelength λ_{pe}.
- drive wakefields resonantly.

⇒ **Seeded self-modulation (SSM)**

AWAKE: Seeding of the instability by

- Placing a laser close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- → Seeding with ionization front

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Laser-Driven Plasma Acceleration Facilities

ALEGRO
Advanced LinEar collider study GROup

Table 2.2: Laser facilities (≳100 TW) performing LWFA R&D in Europe.

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
ELBE [16]	HZDR	Dresden, Ge	30	1	1
GEMINI [17]	STFC, RAL	Didcot, UK	15	0.5	0.05
LLC [18]	Lund Univ	Lund, Se	3	0.1	1
Salle Jaune [19]	LOA	Palaiseau, Fr	2	0.07	1
UHI100 [20]	CEA Saclay	Saclay, Fr	2	0.08	1
CALA* [21]	MPQ	Munchen, Ge	90	3	1
CILEX* [22]	CNRS-CEA	St Aubin, Fr	10-150	1-10	0.01
ELIbeamlines* [23]	ELI	Prague, TR	30	1	10
ILIL* [24]	CNR-INO	Pisa, It	3	0.1	1
SCAPA* [25]	U Strathclyde	Glasgow, UK	8	0.3	5
ANGUS	DESY	Hamburg, Ge	5	0.2	5

Table 2.3: Laser facilities (≳ 100 TW) performing LWFA R&D in Asia

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
CLAPA	PKU	Beijing, PRC	5	0.2	5
CoReLS [28]	IBS	Gwangju, Kr	20-100	1-4	0.1
J-Karen-P* [29]	KPSI	Kizugawa, Jn	30	1	0.1
LLP [30]	Jiao Tong Univ	Shanghai, PRC	5	0.2	10
SILEX*	LFRC	Myanyang, PRC	150	5	1
SULF* [31]	SIOM	Shanghai, PRC	300	10	1
UPHILL [32]	TIFR	Mumbai, In	2.5	0.1	
XG-III	LFRC	Myanyang, PRC	20	0.7	

Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.

Facility	Institute	Location	Gain media	Energy (J)	Peak power (PW)	Rep. rate (Hz)
BELLA [7]	LBNL	Berkeley, CA	Ti:sapphire	42	1.4	1
Texas PW [8]	U. Texas	Austin, TX	Nd:glass	182	1.1	single-shot
Diocles [9]	U. Nebraska	Lincoln, NE	Ti:sapphire	30	1	0.1
Hercules [10]	U. Michigan	Ann Arbor, MI	Ti:sapphire	9	0.3	0.1
Jupiter [11]	LLNL	Livermore, CA	Nd:glass	150	0.2	single-shot

Beam-Driven Plasma Acceleration Facilities

Table 3.1: Overview of PWFA facilities

	AWAKE	CLEAR	FACET-II	FF>>	SparcLAB	EuPR@Sparc	CLARA	MAX IV
operation start	2016	2017	2019	2018	2017 PWFA, LWFA	2022	2020	tbd
unique contribution	protons	rapid access and operation cycle	high energy peak-current electrons, positrons	MHz rep rate 100kW average power 1 fs resolution bunch diagn. FEL gain tests	PWFA with COMB beam, LWFA external injection, test FEL	PWFA with COMB beam, X-band Linac LWFA ext. inj. test FEL	ultrashort e^- bunches	low emittance, short pulse, high-density e^- beam
research topic	HEP	instrumentation irradiation AA technology	high intensity e^-, e^+ beam driven exp.	high average power e^- beam driven exp.	PWFA LWFA FEL	PWFA, LWFA, FEL, other applications	FEL	PWFA, Soft X-FELs
user facility	no	yes	yes	no	no	yes	partially	no
drive beam	p^+	e^-	e^-	e^-	e^-	e^-	e^-	e^-
driver energy	400 GeV	200 MeV	10 GeV	$0.4-1.5$ GeV	150 MeV	600 MeV	240 MeV	3 GeV
ext. inject.	yes	no	no/yes	yes??	no	no	no	no
witness energy	20 MeV	na	tb ugraded	$0.4-1.5$ GeV	150 MeV	600 MeV	na	3 GeV
plasma	Rb vapour	Ar, He capillary	Li oven	H, N, noble gases	H, capillary	H, capillary	He, capillary	H, gases
density [cm^{-3}]	1-10E14	1E16-1E18	1E15-1E18	1E15-1E18	1E16-1E18	1E16-1E18	1E16-1E18	1E15-1E18
length	10 m	5-20 cm	10-100 cm	1-30 cm	3 cm	$>$ 30 cm	10-30 cm	10-50cm
plasma tapering	yes	na	yes	yes	yes	yes		yes
acc. gradient	1 GeV/m average	na	10+ GeV/m peak	10+ GeV/m peak	$>$1 GeV/m??	$>$1 GeV/m??	na	10+ GeV/m peak
exp. E gain	1+ GeV	na	$\approx$10 GeV	$\approx$1.5 GeV	40 MeV ??	$>$ 500 MeV	na	3 GeV

FACET, SLAC, US – Electrons as Driver

Premier R&D facility for PWFA: Only facility capable of e^+ acceleration

- **Timeline:**
  - Commissioning (2011)
  - Experimental program (2012-2016)
- **Key PWFA Milestones:**

✓ Mono-energetic e^- acceleration
✓ High efficiency e^- acceleration
✓ First high-gradient e^+ PWFA
✓ Demonstrate required emittance, energy spread

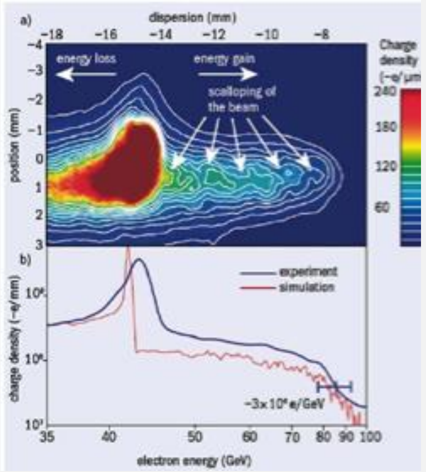
➔ **FACET-II started in 2021**

- Facility hosted more than 200 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields
- Unique opportunity to develop future leaders

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

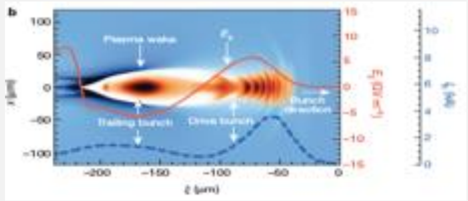
*I. Blumenfeld et al, Nature 455, p 741 (**2007**)*

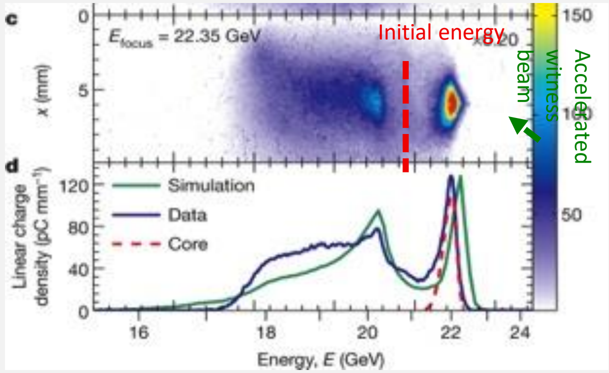
→ **gradient of 52 GV/m**



High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

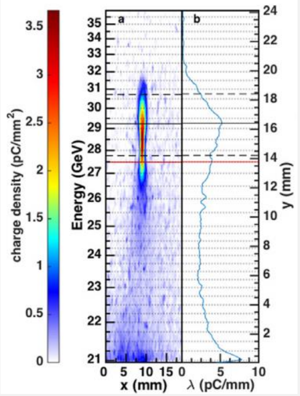
*M. Litos et al., doi, Nature, 6 Nov **2014**, 10.1038/nature 13882*





70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient ➔ **Up to 30% transfer efficiency, ~2% energy spread**

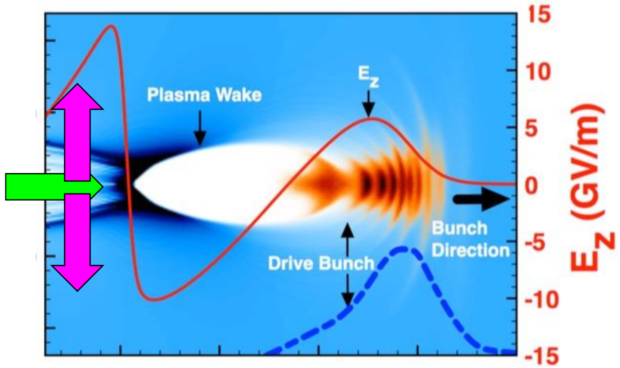
9 GeV energy gain in a beam-driven plasma wakefield accelerator
*M Litos et al **2016** Plasma Phys. Control. Fusion 58 034017*



Positron Acceleration, FACET

Positrons for high energy linear colliders: **high energy, high charge, low emittance**.

Electron-driven blowout wakes:



But the field is defocusing in this region.

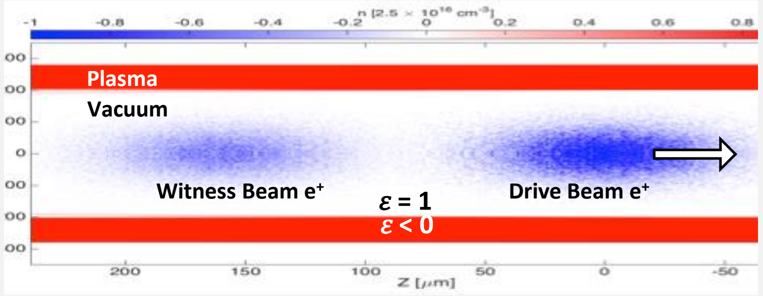
First demonstration of positron acceleration in plasma (FFTB)

*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Energy gain of 5 GeV. Energy spread can be as low as 1.8% (r.m.s.).

*S. Corde et al., Nature **524**, 442 (2015)*

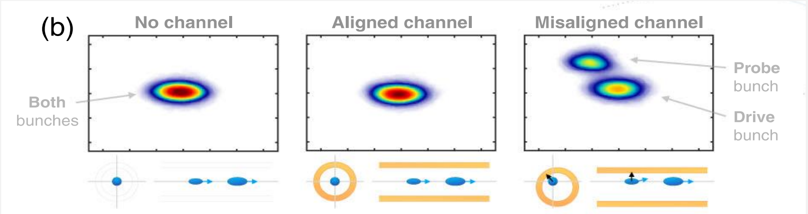
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.
S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



There is no plasma on-axis, and therefore no complicated forces from plasma electrons streaming through the beam.

Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

*C. A. Lindstrøm et. al. Phys. Rev. Lett. 120 124802 (**2018**).*



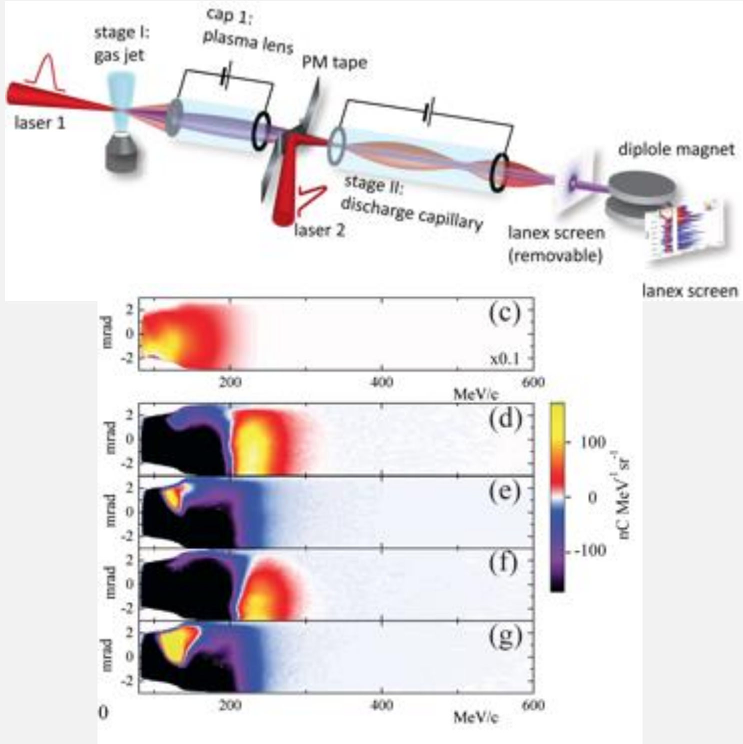
➔ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

BELLA, Berkeley Lab, US– Laser as Driver

Laser Driven Plasma Wakefield Acceleration Facility: Today: PW laser!

Multistage coupling of independent laser-plasma accelerators

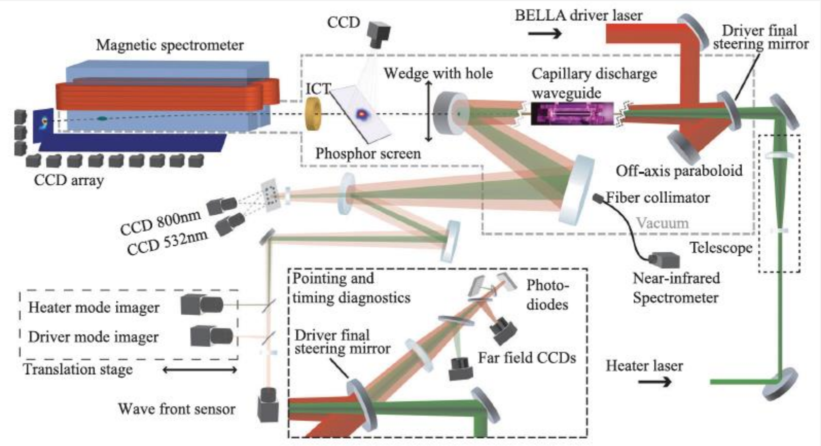
S. Steinke, Nature ***530****, 190 (2016)*



Staging demonstrated at 100MeVs level.

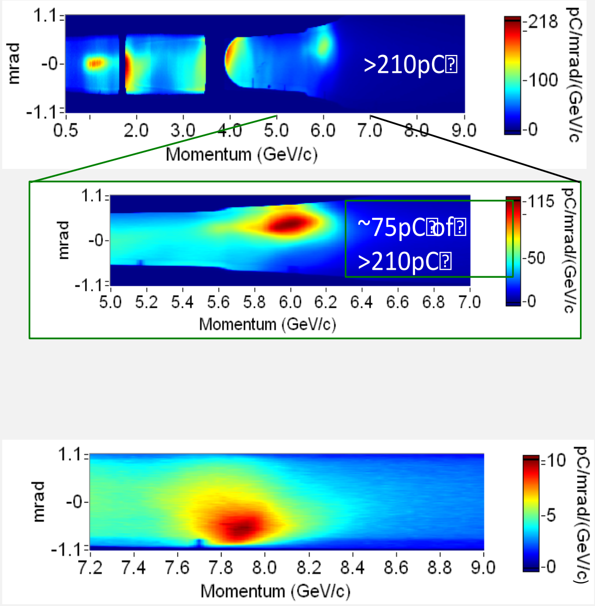
Petawatt laser guiding and electron beam **acceleration to 8 GeV** in a laser-heated capillary discharge waveguide

A.J.Gonsalves et al., Phys.Rev.Lett. ***122****, 084801 (2019)*



Laser heater added to capillary

Electron spectra, up to 6-8 GeV



→ path to 10 GeV with continued improvement of guiding in progress

FLASHForward>>, DESY

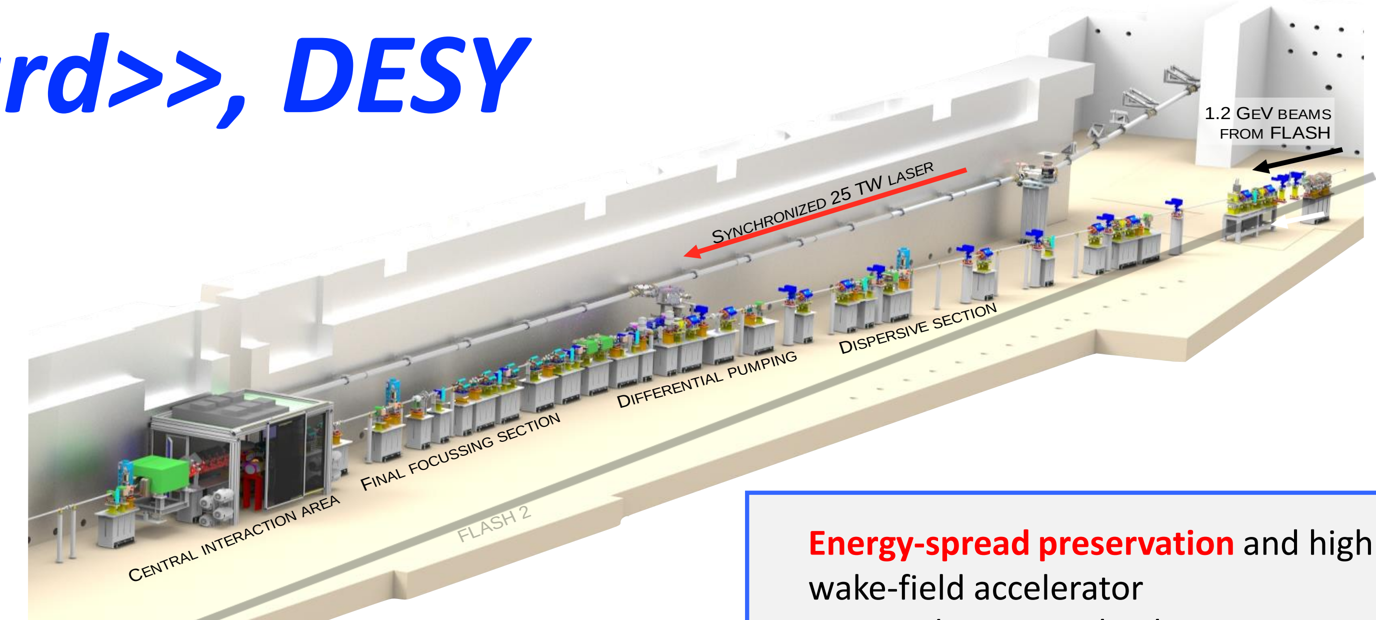
→ **FLASH** is an FEL user facility

- 10% of beam time dedicated to generic accelerator research and development

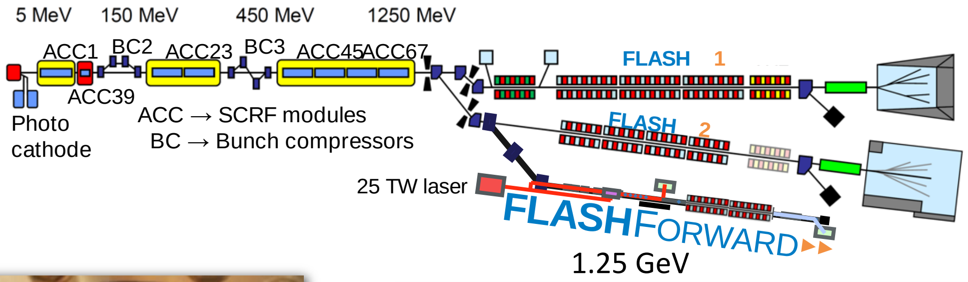
→ **FLASH**Forward▸▸ is a beam line for PWFA research

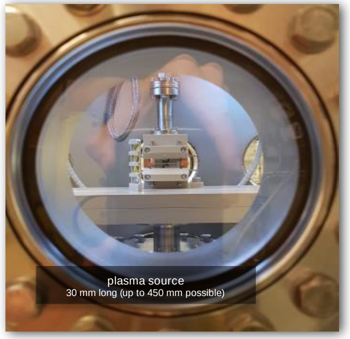
→ Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:

- ≲ **1.25 GeV energy** with a few **100 pC at ~100 fs** rms bunch duration, up to 1MHz repetition rate, few kW average power



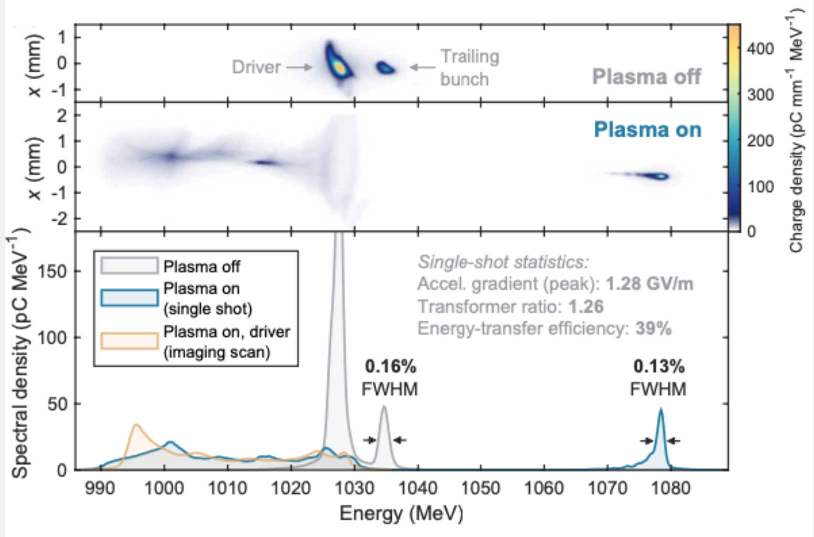
→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)





Energy-spread preservation and high efficiency in a plasma-wake-field accelerator

C.A. Lindstrøm et al., Phys.Rev.Lett. ***126****, 014801 (****2021****)*



Transfer efficiency **42+/-4%** with **0.2% energy spread**,
Up to **70%** when allowing energy spread increase

State of the Art and Goals for HEP Collider

	Current	FEL (Intermediate Goal)	Collider (Final Goal)
Charge (nC)	0.01 – 0.1	0.01 – 0.1	0.1– 1
Energy (GeV)	9	0.1 – 10	1000
Energy spread (%)	0.1	0.1	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	0.1– 1	0.01
Staging	single, two	single, two	multiple
Wall plug efficiency (%)	0.1	<0.1 - 10	10
Rep Rate (Hz)	10	10^1 - 10^6	10^4 - 10^5
Avg. beam power (W)	10	10^1 - 10^6	10^6
Acc. Distance (m)/stage	1	1	1 – 5
Continuous run	24/1	24/1 – 24/7	24/365
Parameter stability	1%	0.1%	0.1%
Simulations	days	days - 10^7	improvements by 10^7
Positron acceleration	acceleration		emittance preservation
Plasma cell (p-driver)	10 m		100s m
Proton drivers	SSM, acceleration		emittance control

Various important milestones have been and will be achieved in internationally leading programmes at:
CERN, CLARA, CNRS, DESY, various centres and institutes in the Helmholtz Association, INFN, LBNL, RAL, Shanghai XFEL, SCAPA, SLAC, Tsinghua University and others.

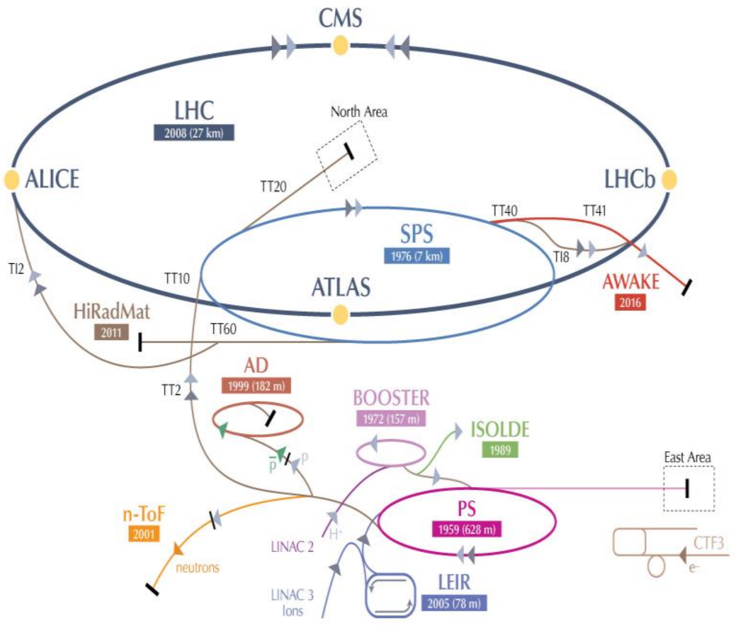
New European research infrastructures involving lasers and plasma accelerator technology have been driven forward in recent years, namely ELI and EuPRAXIA, both placed on the ESFRI roadmap.

The distributed RI **EuPRAXIA** as well as the aforementioned internationally leading programmes **will pursue several important R&D milestones and user applications for plasma accelerators.**

Outline

- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment
- Applications with AWAKE-Like Scheme
- Outlook

AWAKE at CERN



Advanced WAKEfield Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Collaboration of 23 institutes world-wide
- Approved in August 2013

AWAKE Run 1 (2016-2018):

✓ 1st milestone: Demonstrate seeded self-modulation of the proton bunch in plasma (2016/17)

✓ 2nd milestone: Demonstrate electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

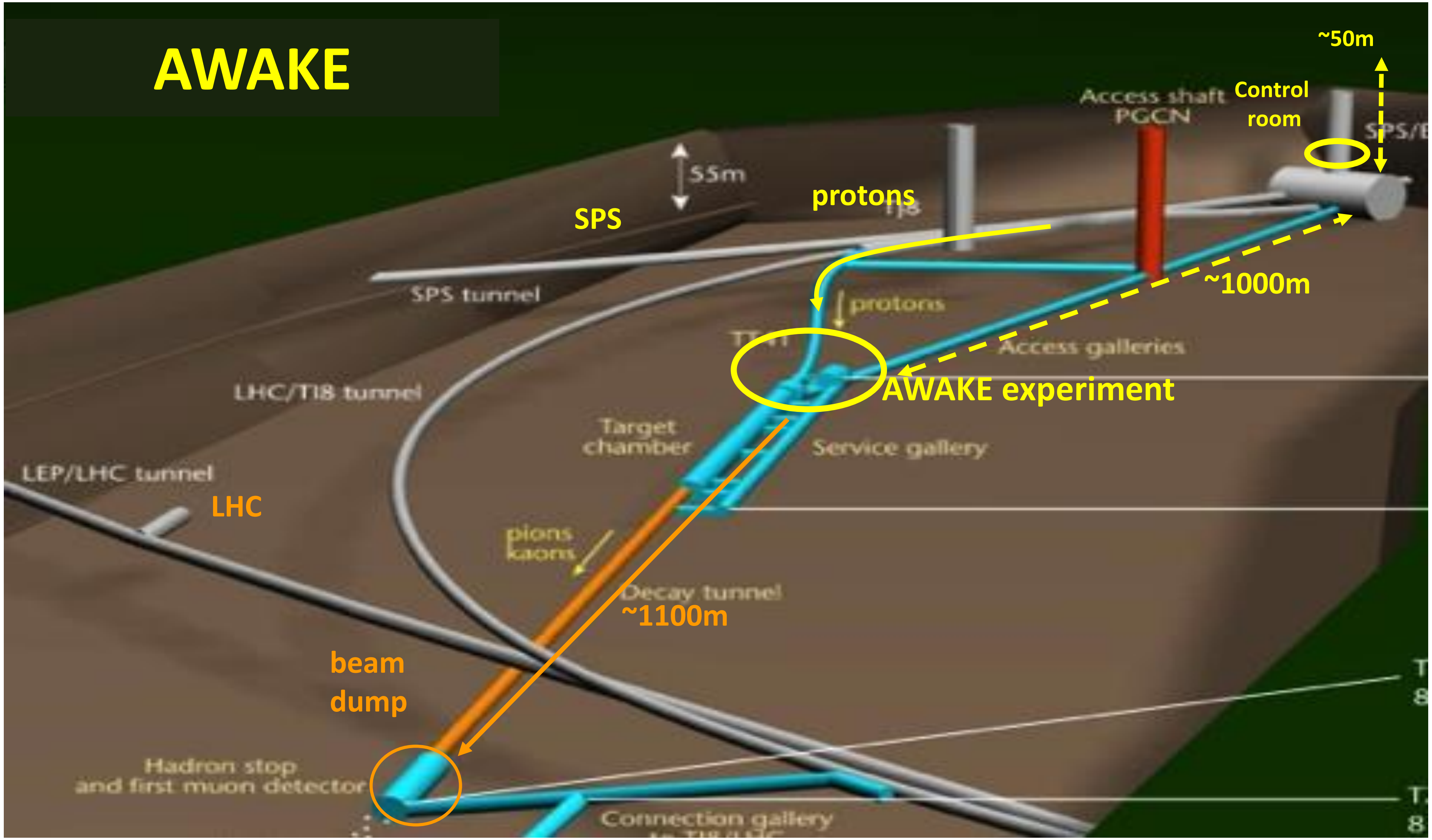
AWAKE Run 2 (2021 – ~2029):

Accelerate an electron beam to high energies (gradient of 0.5-1GV/m) while preserving the electron beam quality and demonstrate scalable plasma source technology.

Once AWAKE Run 2 demonstrated: First application of the AWAKE-like technology:

Fixed target experiments for e.g. dark photon search.

AWAKE at CERN



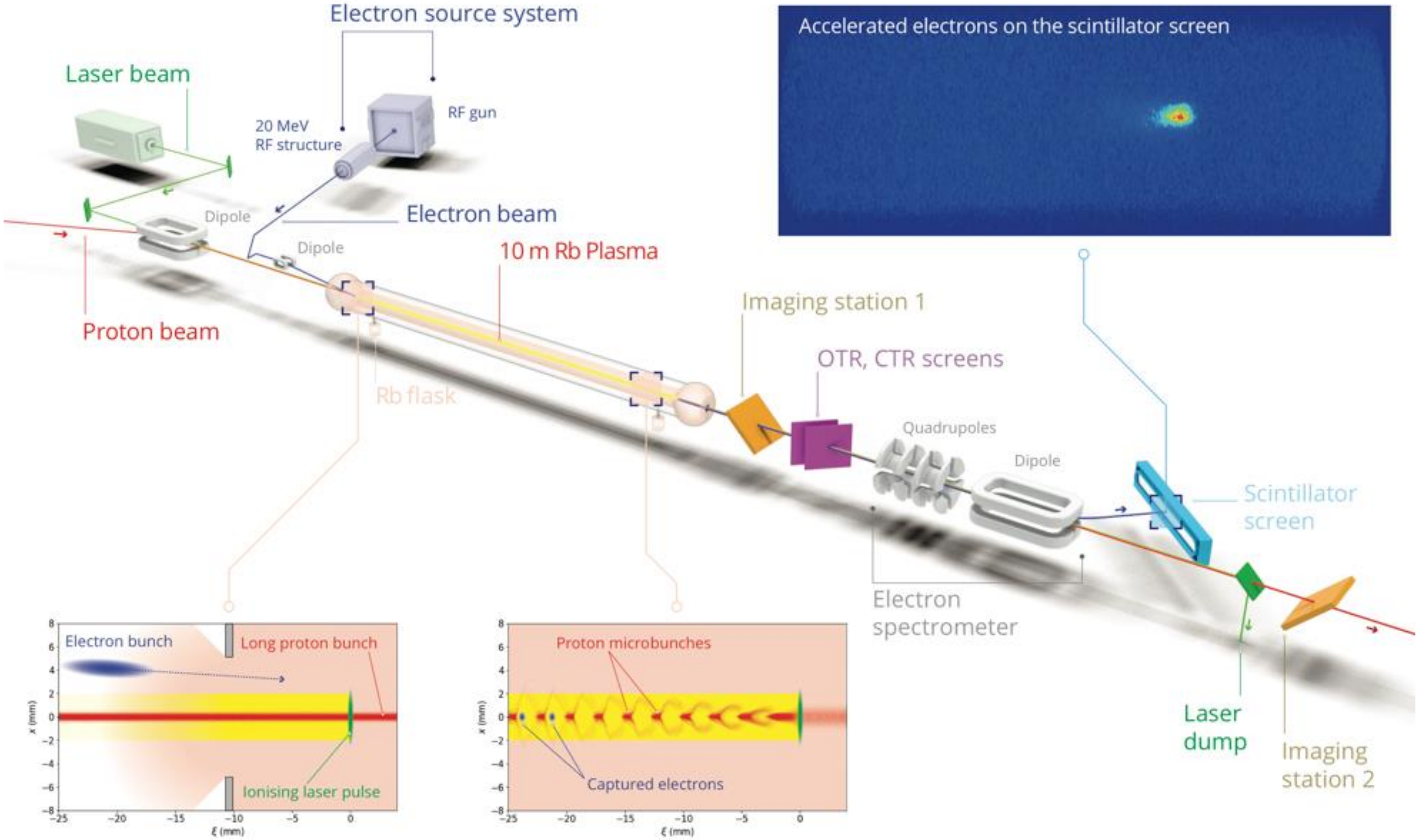
AWAKE installed in CERN underground area

AWAKE Collaboration: 23 Institutes World-Wide

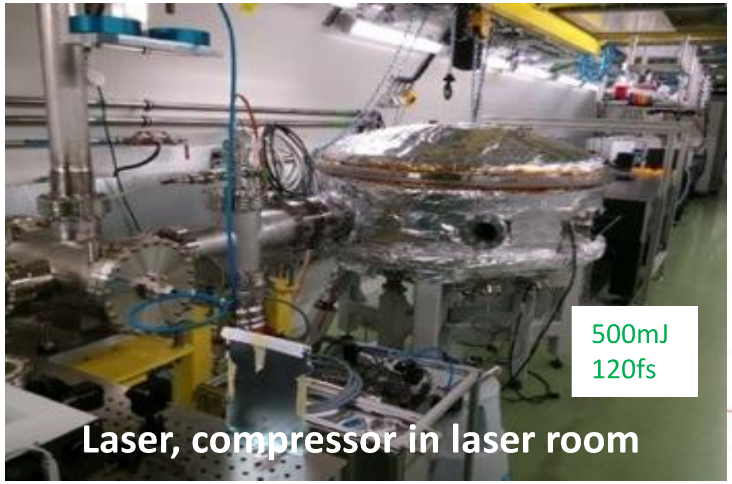
- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Sweden
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

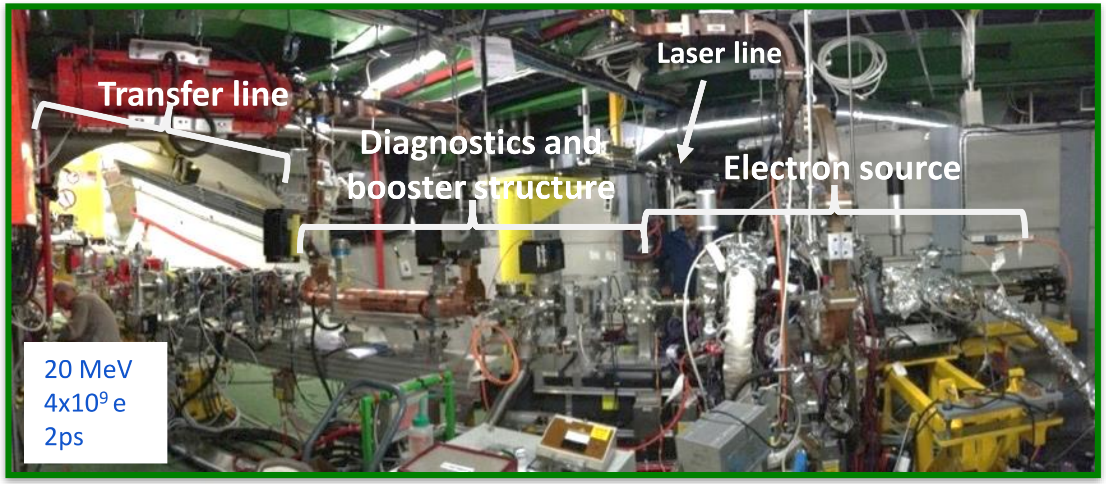
AWAKE Experiment

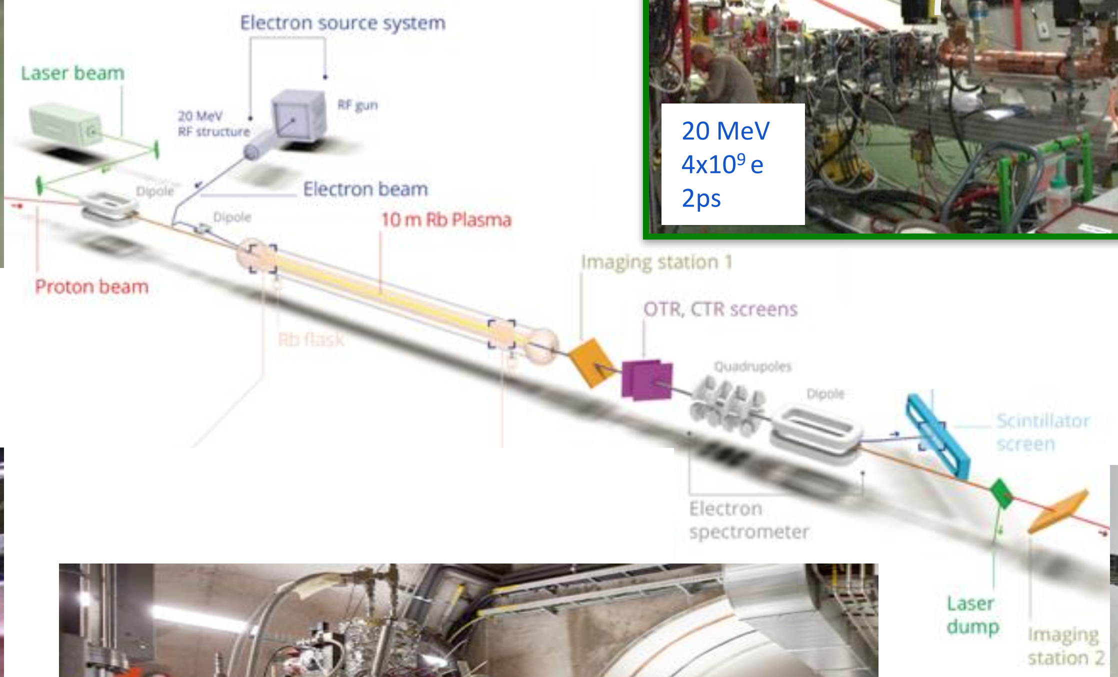
AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

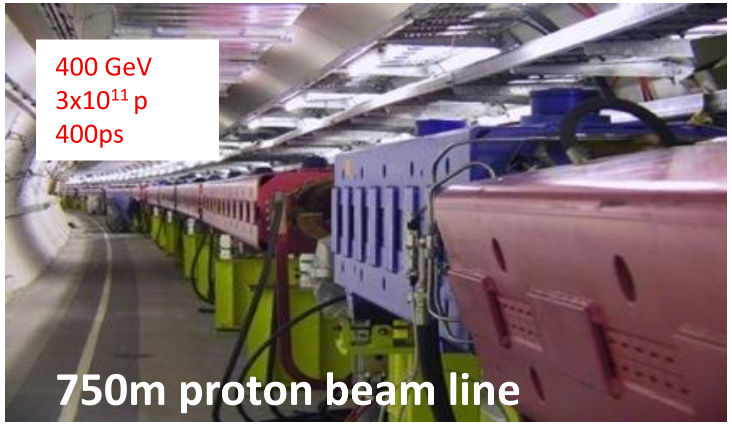


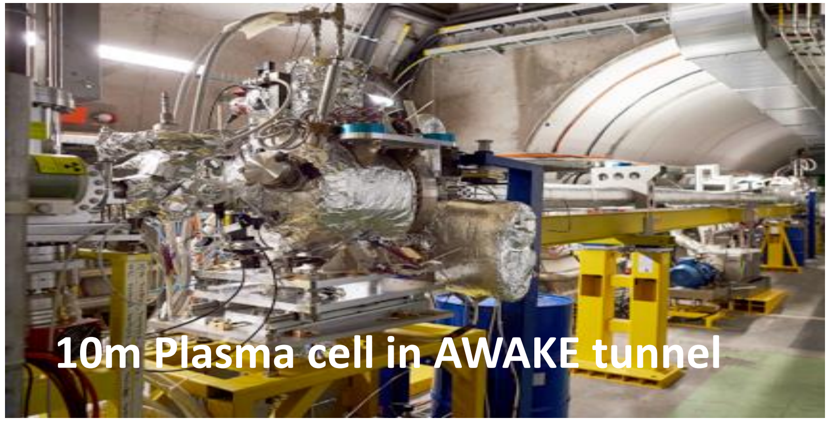
Key Ingredients of AWAKE



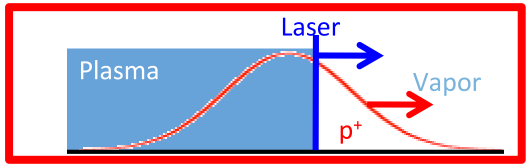




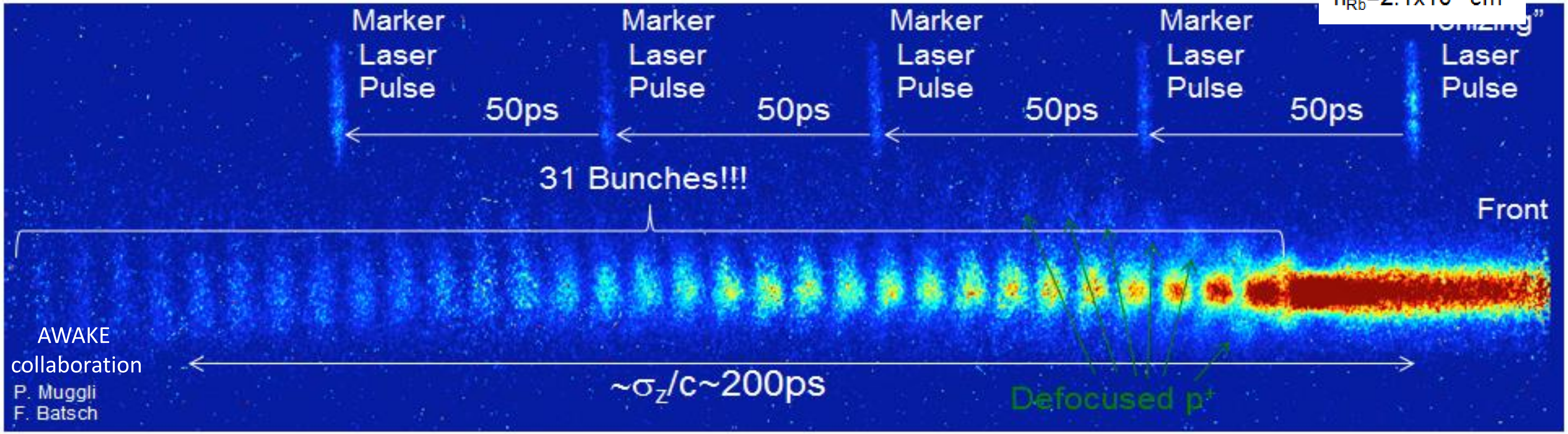




Results Run 1: Direct Seeded Self-Modulation Measurement



$n_{Rb}=2.1\times10^{14}cm^{-3}$



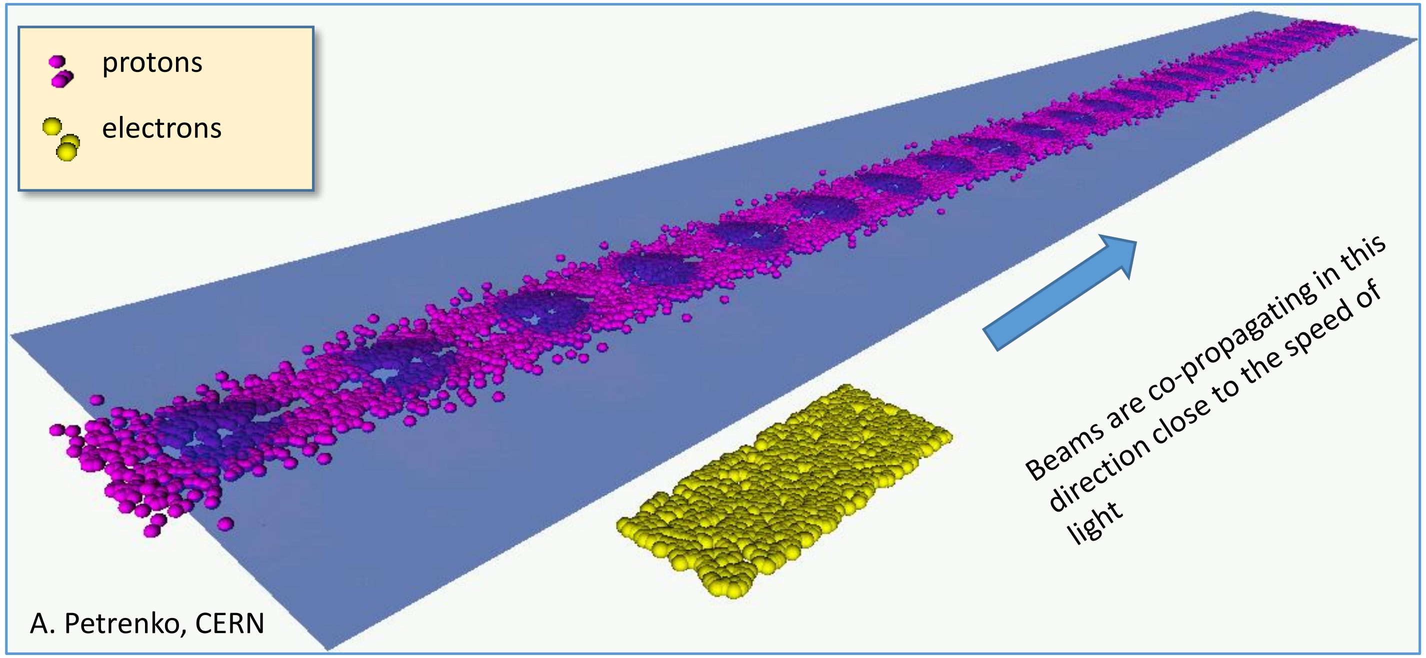
- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the μ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

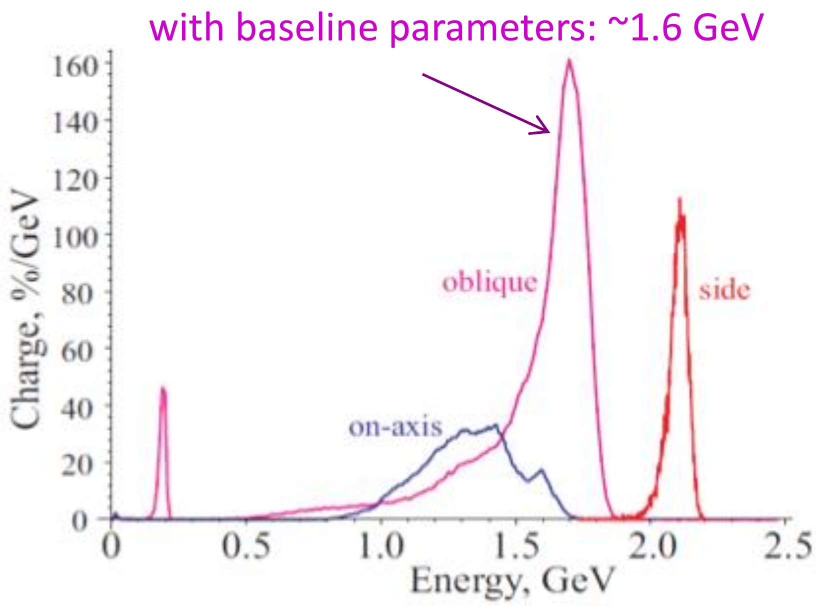
→ 1st AWAKE Milestone reached

AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Collaboration), 'Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett. July 30 (2020).
A.A. Gorn, M. Turner et al. (AWAKE Collaboration), Plasma Phys. Control Fusion, Vol. 62, Nr 12 (2020).
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

AWAKE Run 1: Electron Acceleration Results

Electron acceleration after 10m:
What we expect with the AWAKE Run 1 setup:

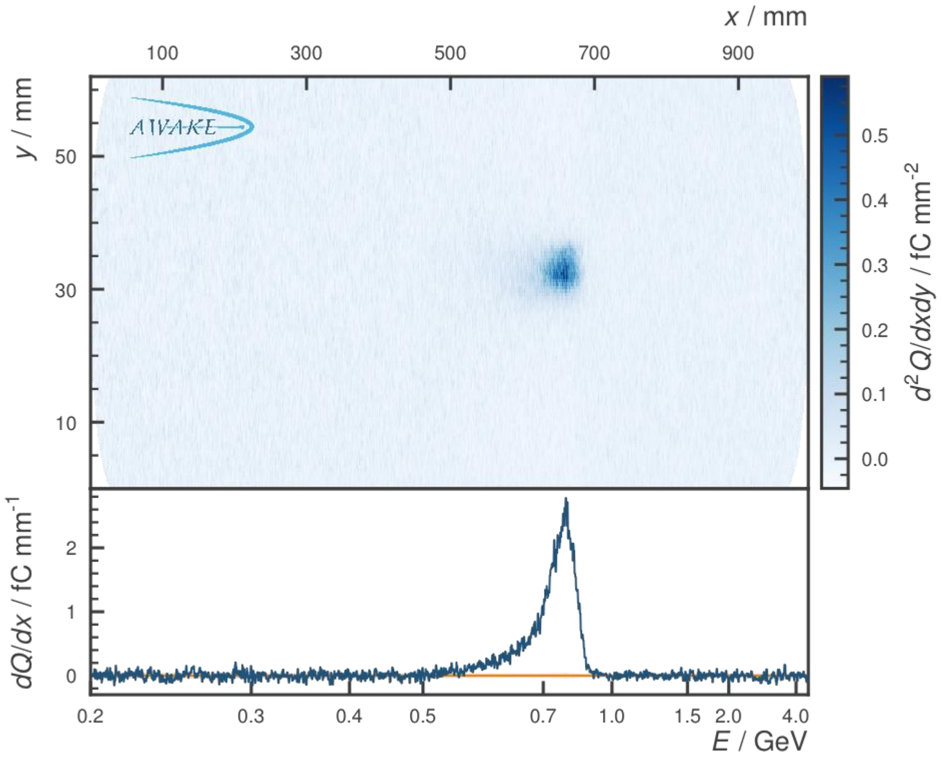




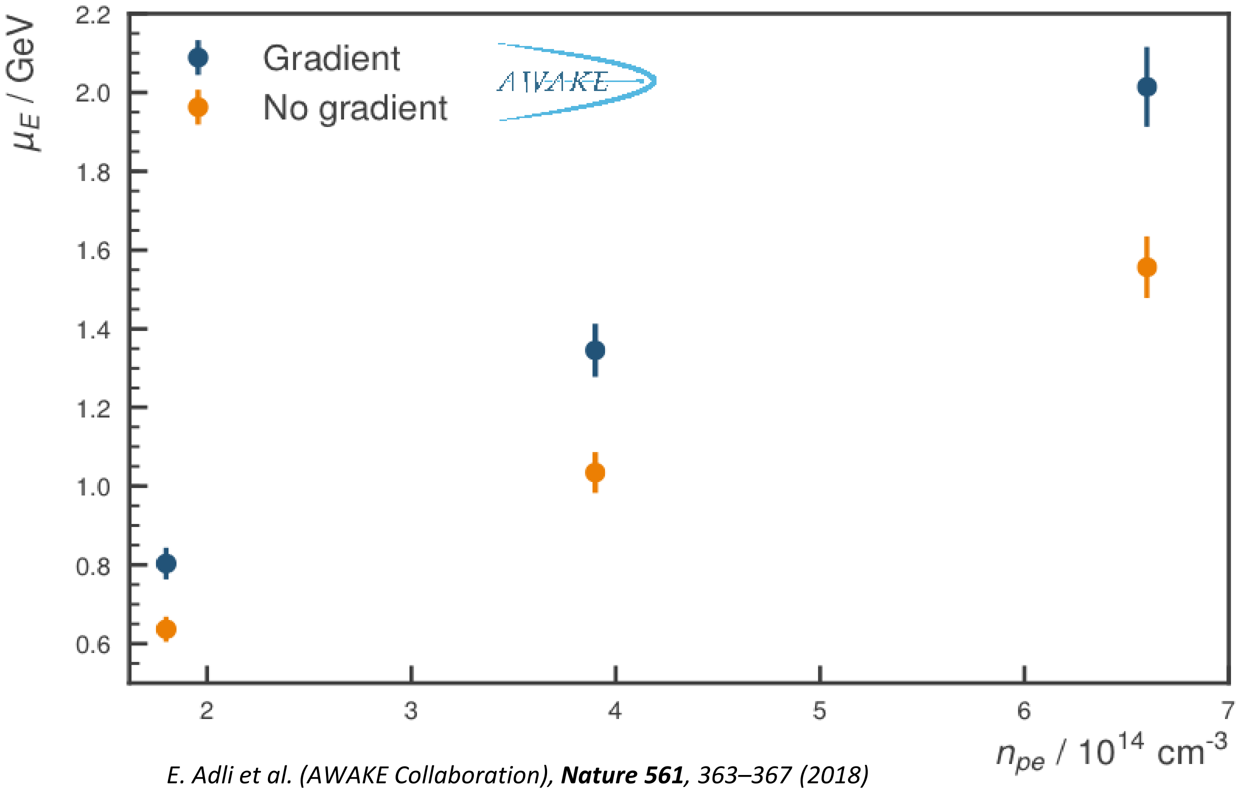
A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

AWAKE Run 1: Electron Acceleration Results

Event at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m density gradient. → Acceleration to 800 MeV.



- **Acceleration up to 2 GeV** has been achieved.
- Charge capture up to 20%.

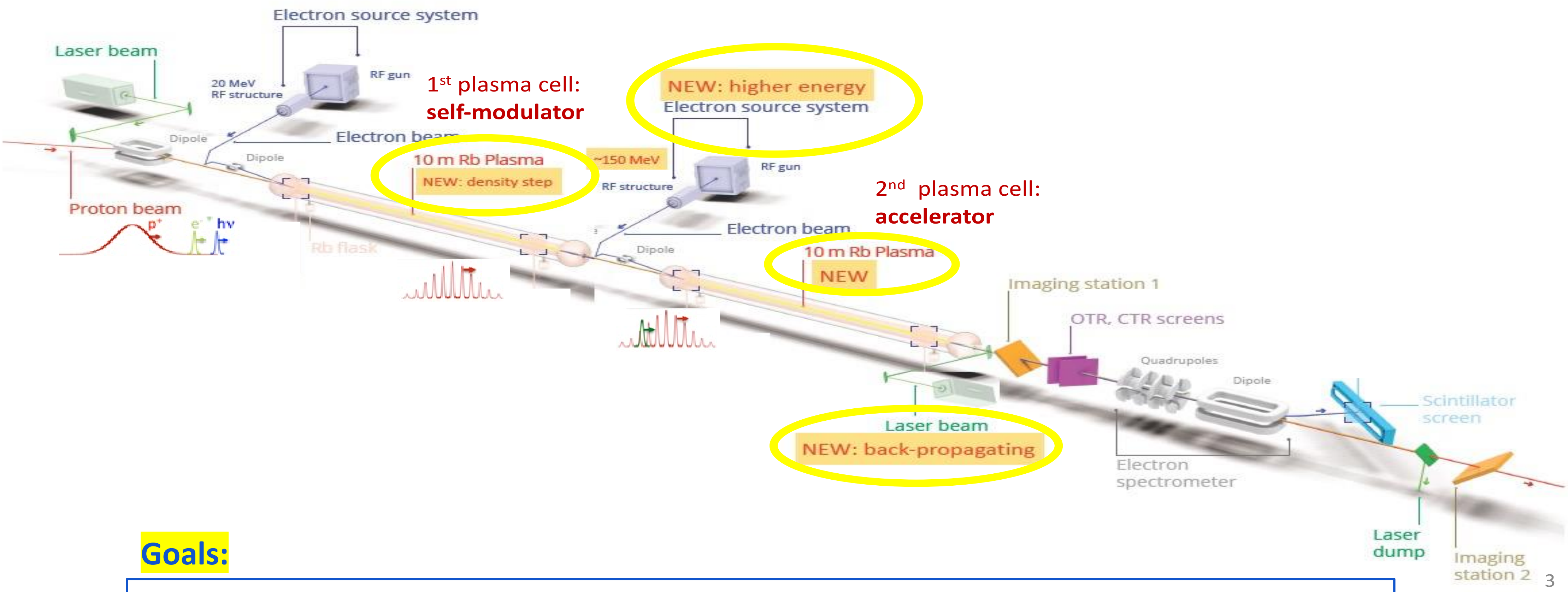


*E. Adli et al. (AWAKE Collaboration), **Nature 561**, 363–367 (2018)*

→ 2nd AWAKE Milestone reached

AWAKE Run 2

- ➔ **Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!**
- ➔ **Start 2021, program goes beyond CERN Long Shutdown 3 (2027+)**!



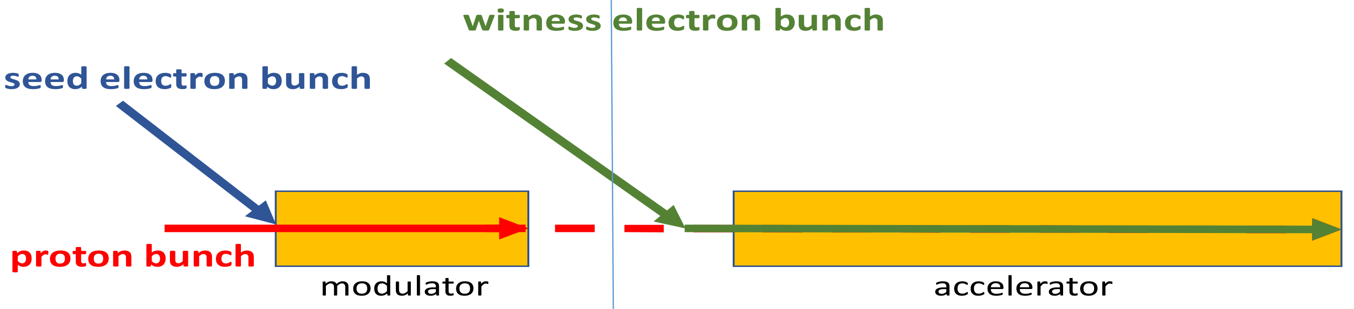
Goals:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon prototype)

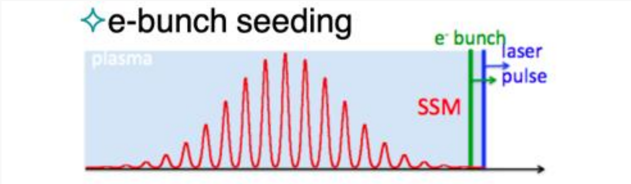
AWAKE Run 2



Optimize self-modulation of the proton bunch

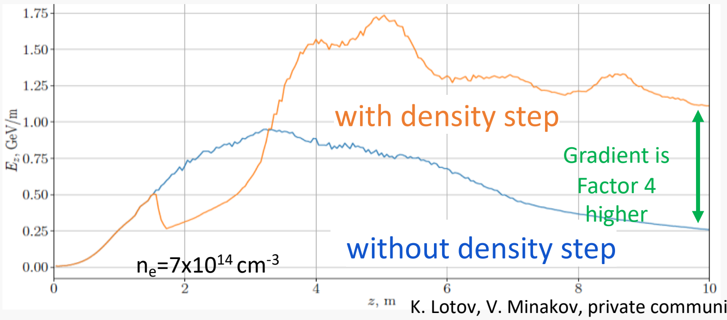
Optimize acceleration of electrons in p-driven plasma wakefield

AWAKE Run 2a: self-modulation of entire p-bunch seeded with an e-bunch



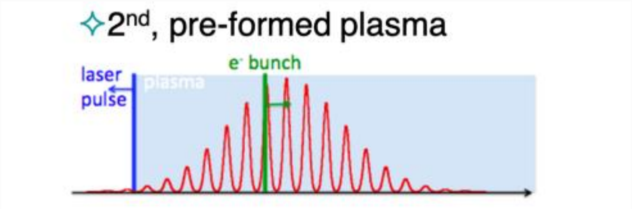
AWAKE Run 2b: stabilization of the micro-bunches with a density step in the plasma cell and maintain high gradient

Gradient in 1st plasma source (self-modulator)

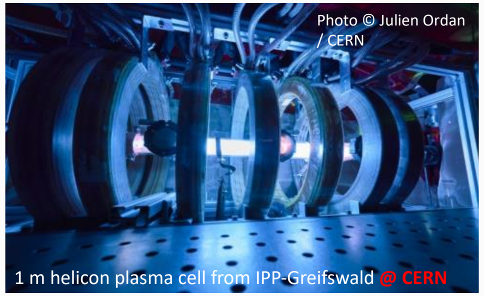


K. Lotov, V. Minakov, private communication

AWAKE Run 2c: electron acceleration and emittance control



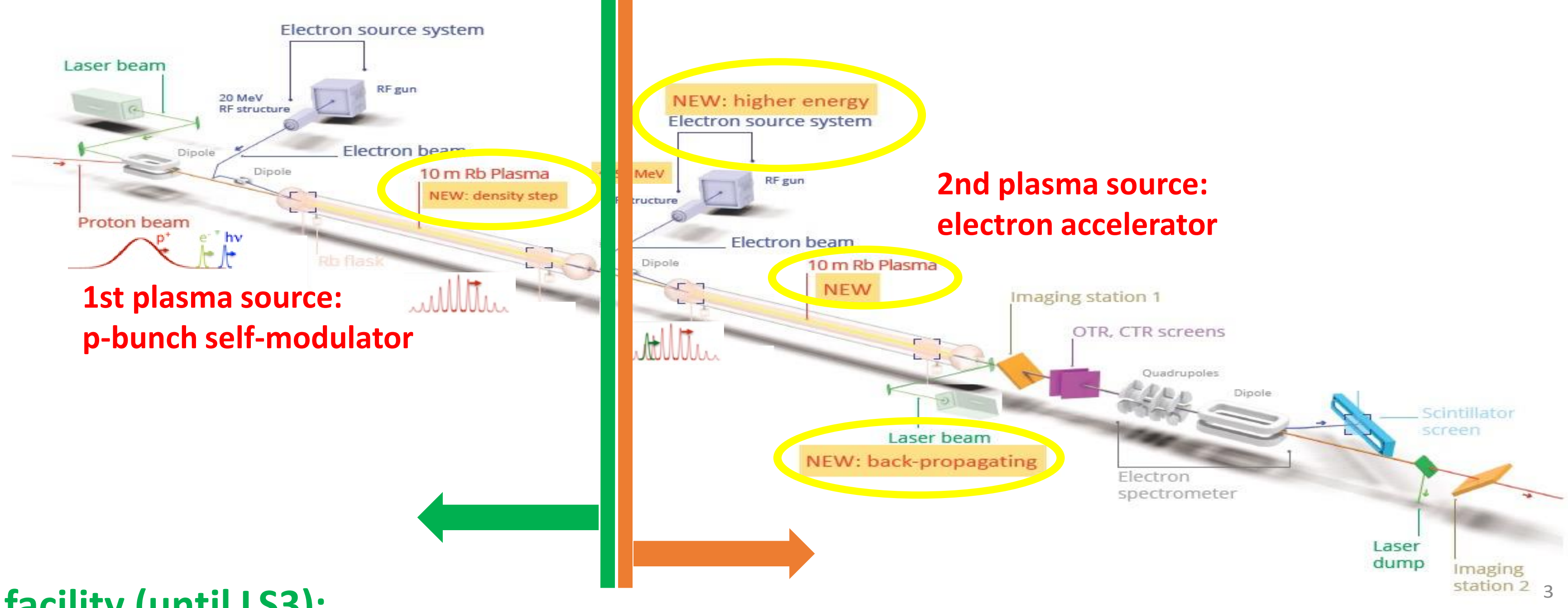
AWAKE Run 2d: scalable plasma sources



AWAKE Run 2 Program

AWAKE Run 2a and Run 2b until LS3 (2025):
Optimize self-modulation of the proton bunch

AWAKE Run 2c and Run 2d after LS3 (2027+) :
Optimize acceleration of electrons in p-driven plasma wakefield



In existing AWAKE facility (until LS3):

Run 2a: demonstrate electron seeding of self-modulation in first plasma cell (2021/22)
Run 2b: demonstrate the stabilization of the micro-bunches with a density step in the plasma cell (2023/2024)

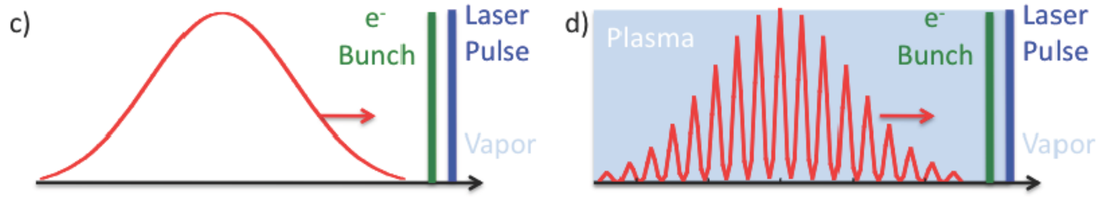
In extended AWAKE facility: (after LS3 2027+)

Run 2c: demonstrate electron acceleration and emittance preservation
Run 2d: demonstrate scalable plasma sources

During CERN Long Shutdown 3:
dismantling of CNGS area
Installation of 2nd plasma source, 2nd electron beam system…

AWAKE Run 2a – First Results

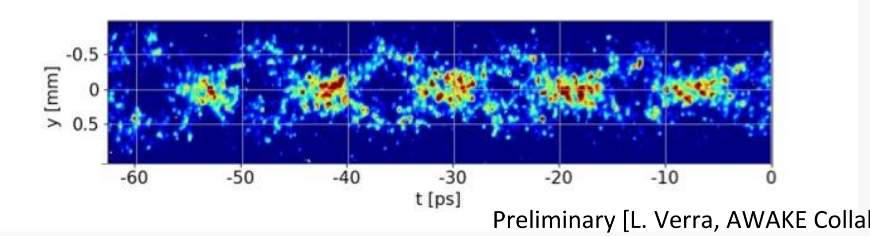
Goal: Electron bunch seeding to modulates entire proton bunch with phase reproducibility



1st plasma cell: **self-modulator**

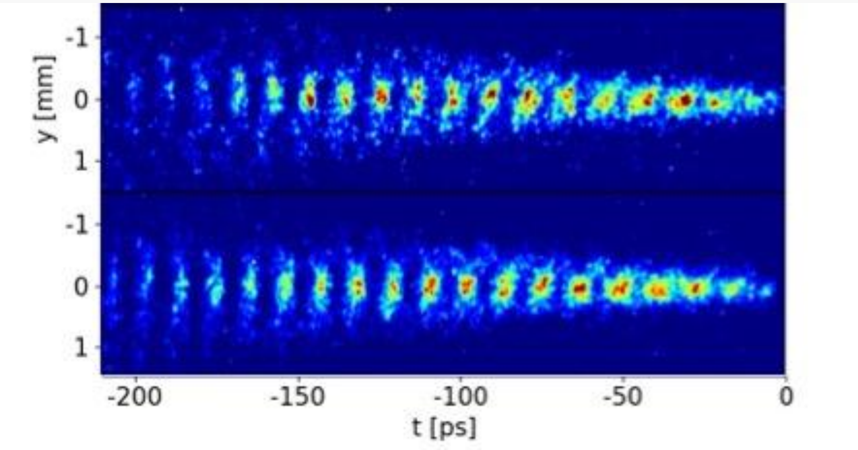
→ **Physics program of 2021:**
Experimental demonstration that the 19 MeV electron bunch seeds the proton bunch self-modulation in plasma:

The time structure of the microbunch train is **reproducible**



Preliminary [L. Verra, AWAKE Collaboration]

The electron bunch timing **controls** the timing of the microbunches and the phase of the wakefields

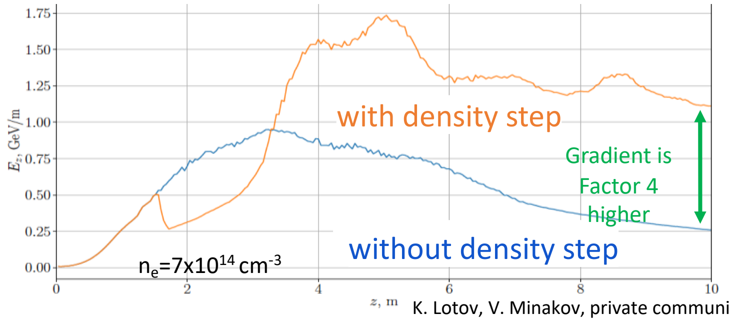


→ **Run 2a will continue in 2022 with further important studies!**

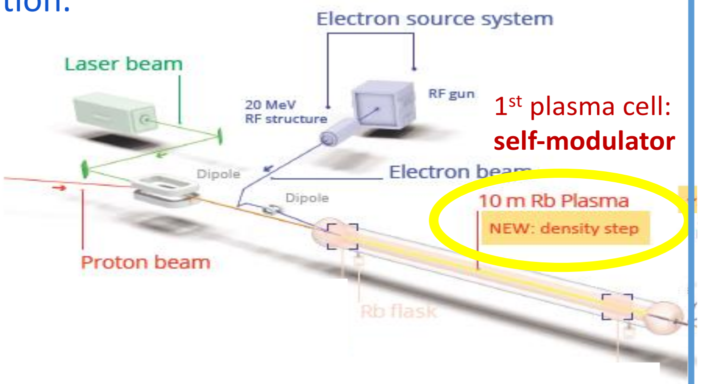
AWAKE Run 2b

- In constant-density plasma, wakefield amplitude decreases after saturation.
- In a plasma with density step within the SM grow: wakefield amplitude **maintains larger** after saturation.

Gradient in 1st plasma source (self-modulator)



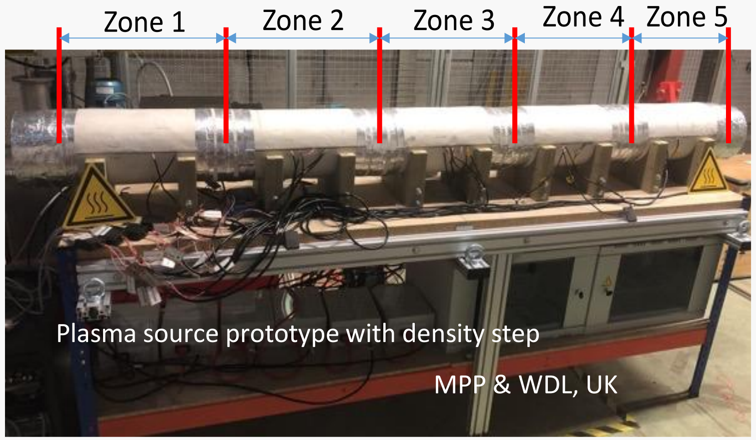
K. Lotov, V. Minakov, private communication



→ Physics Program 2023/2024: Demonstrate the stabilization of the micro-bunches with a density step.

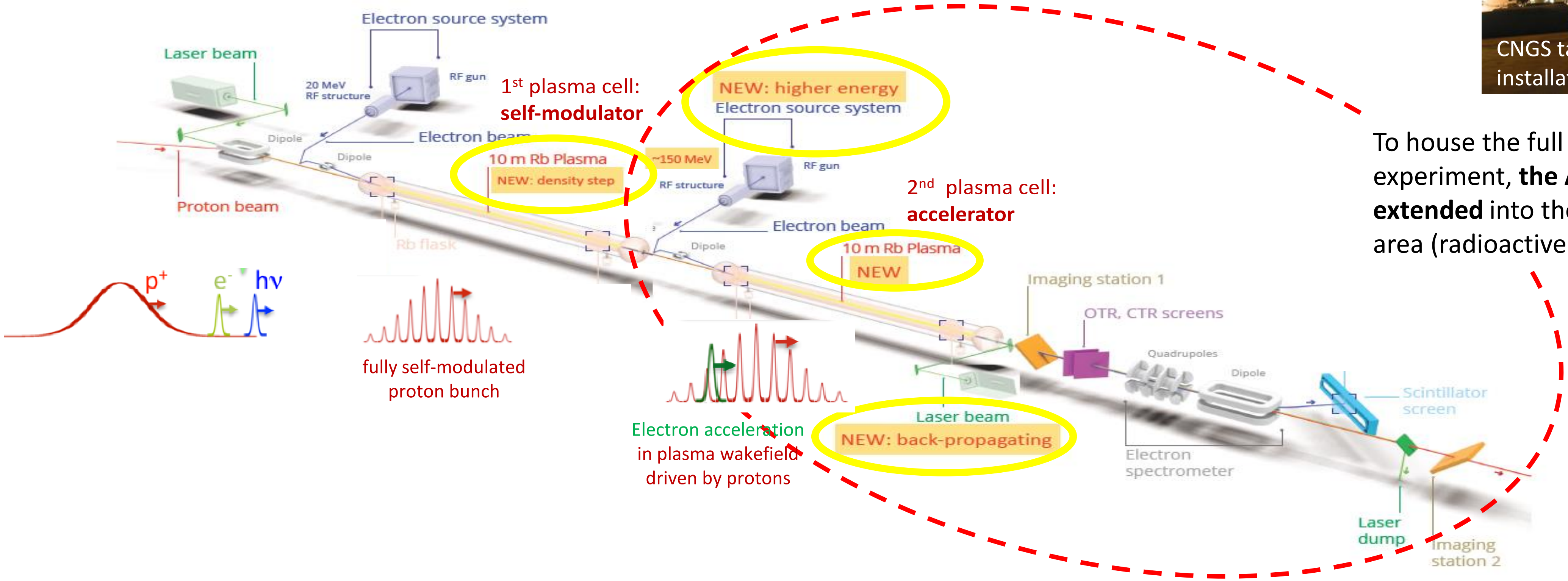
→ new plasma source with density step capability

→ novel plasma diagnostics to allow measurement of plasma 'wave' directly



AWAKE Run 2c

- Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)



To house the full length of the Run 2 experiment, **the AWAKE area must be extended** into the former CNGS target area (radioactive!)

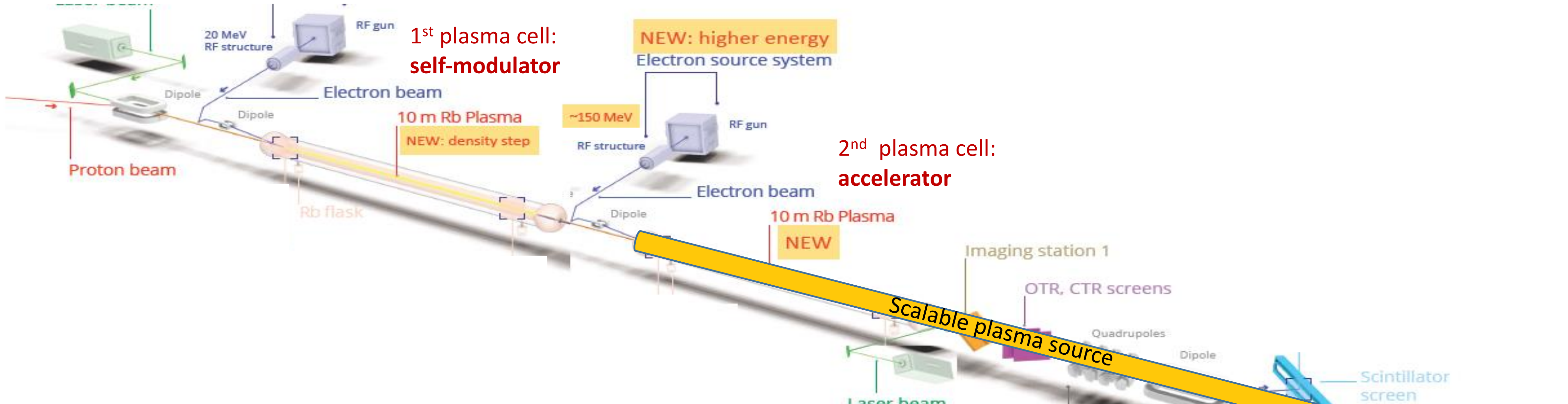
- New electron source and beam line, reuse run 1 e-source
- New plasma cell (Accelerator cell), reuse 2b self-modulator
- New laser to 2nd plasma cell (back-propagating)
- New diagnostics

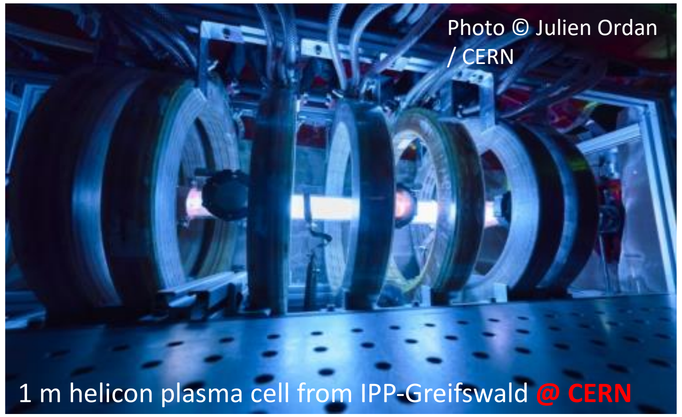
➔ **Facility extension and installation: 2025/26/27**

➔ **Physics program: 2027/28/…**

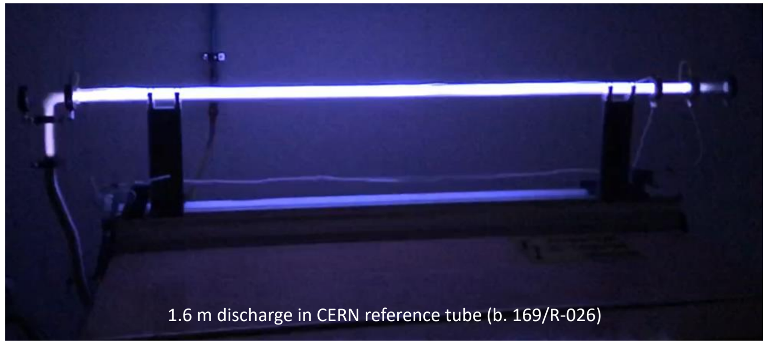
AWAKE Run 2d: Demonstrate Scalable Plasma Sources

Today: Laboratory developments of scalable plasma sources in dedicated plasma labs
Aim: Propose a design for a scalable, several meter-long plasma cell for Run 2d.
Final Goal: Use this technology to build a 50-100m long plasmas source and use it for **first applications (~2029)**





1 m helicon plasma cell from IPP-Greifswald @ CERN


1.6 m discharge in CERN reference tube (b. 169/R-026)

➔ **1m prototypes at CERN!!**

Outline

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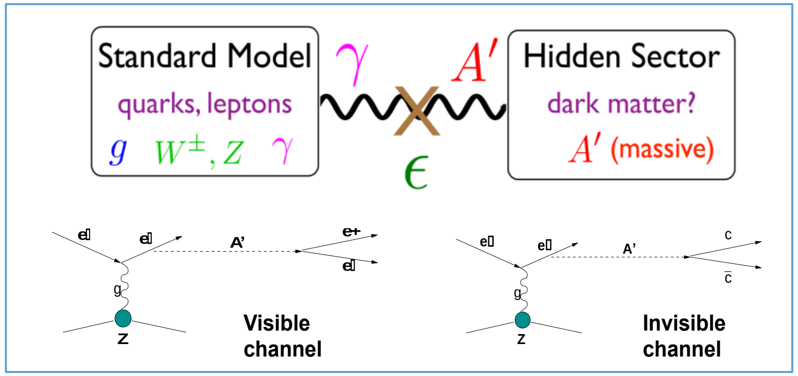
Applications with AWAKE-Like Scheme

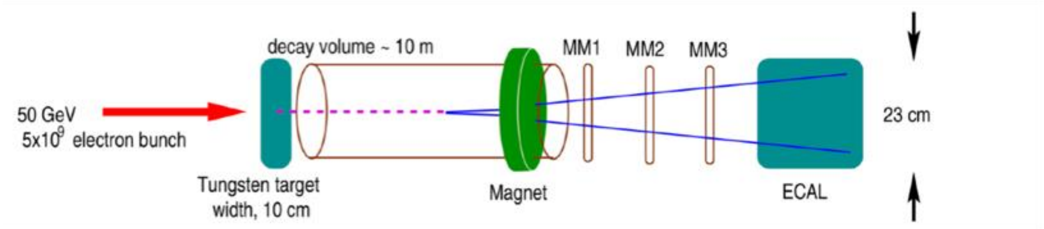
➔ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

First Application: Fixed target test facility:

→ Deep inelastic scattering, non-linear QED, **search for dark photons**

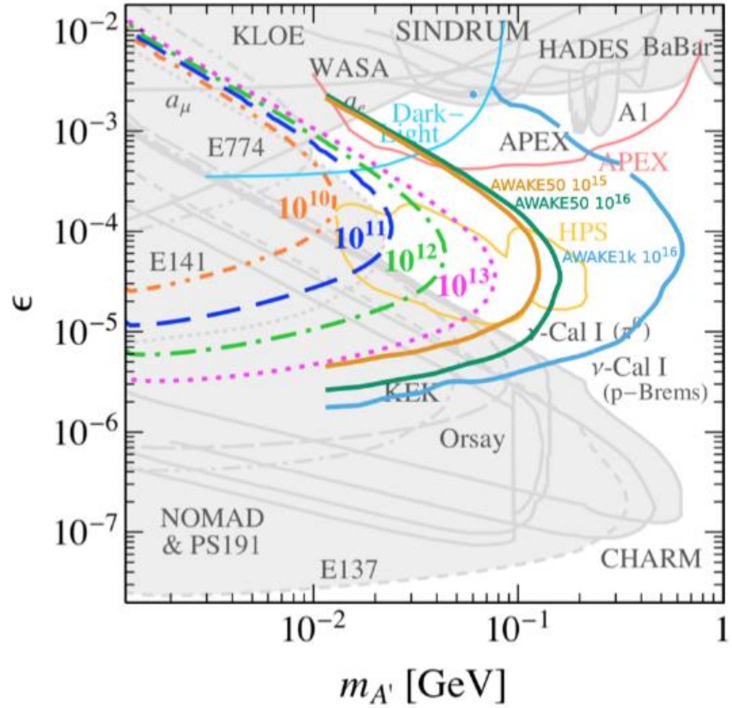


→ Decay of dark photon into visible particles (e.g. e+/e-)
→ Energy and flux is important
→ Relaxed parameters for emittance



Experimental conditions modeled on NA64 experiment.

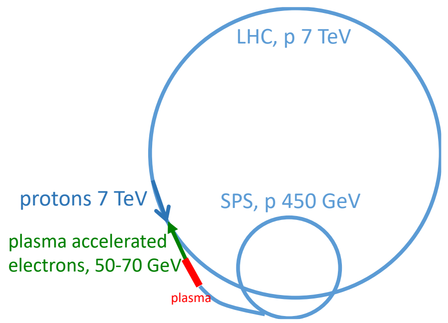
→ Use bunches from SPS with 3.5 E11 protons every ~5sec, → electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons** (compared to NA64)



→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

Applications with AWAKE-Like Scheme

- **PEPIC:** Low-luminosity version of LHeC (50 GeV electrons)
  - Use the SPS to drive electron bunches to 50 GeV and collide with protons from the LHC
  - Modest luminosity → only interesting should the LHeC not go ahead



- **EIC:**
  - use the RHIC-EIC proton beam to accelerate electron

- **3 TeV VHEeP**
  - use the LHC protons to accelerate electrons to 3 TeV and collide with protons from LHC with 7 TeV
  - Yields centre-of-mass energy of 9 TeV, Luminosity is relatively modest ~1028 – 10^{29} cm^{-2} s^{-1}, i.e. 1bp^{-1}/yr.
  - New energy regime means new physics sensitivity even at low luminosities.

- **Fixed target** variants with these electron beams

Summary and Outlook

→ Plasma wakefield acceleration is an exciting and growing field with many encouraging results and a huge potential.

- → AWAKE: Proton-driven plasma wakefield acceleration interesting because of large energy content of driver. Modulation process means existing proton machines can be used.

→ Current and planned facilities (Europe, America, Asia) explore different advanced and novel accelerator concepts and proof-of-principle experiments and address beam quality challenges and staging of two plasmas.

→ Coordinated R&D program for dedicated international facilities towards addressing HEP challenges are needed over the next 5 to 10 years.

- → As follow-up from the Update of the European Strategy on Particle Physics, the Plasma wakefield acceleration community has prepared a roadmap towards a high-energy collider based on advanced acceleration technologies.

Outlook:

→ **Near-term goals:** the laser/electron-based plasma wakefield acceleration could provide near term solutions for FELs, medical applications, etc.

→ **Mid-term goal:** the AWAKE technology could provide particle physics applications.

→ **Long-term goal:** design of a high energy electron/positron/gamma linear collider based on plasma wakefield acceleration.